

STUDY OF DYNAMICS OF MINOR
CONSTITUENTS IN THE THERMOSPHERE

by

Joe M. Straus and Lee A. Christopher

OCTOBER 1978

Addendum to Report dated May 1977

Prepared under Contract No. NAS1-14102

by

Space Sciences Laboratory
The Ivan A. Getting Laboratories
THE AEROSPACE CORPORATION
El Segundo, CA 90245

for

National Aeronautics and Space Administration



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ABSTRACT

This Addendum describes the continuation of numerical studies dealing with the dynamics of minor constituents in the earth's thermosphere. Previous investigations of the distribution of thermospheric helium were repeated, making use of the Jacchia (1977) model in place of CIRA (1972) for specifying the background gas temperature and pressure. Changes in the global transport of helium under solstice conditions caused by a small increase in the latitudes at which the background gas pressure extrema occur lead to much better agreement of the model predictions with data taken by the mass spectrometers on board the ESRO-4 and OGO-6 satellites. Development of a three-component (N_2 , O_2 , and O) model of the thermosphere, initiated under funding by Aerospace Corporate Programs for Research and Experimentation, was continued. The model was applied to a study of the global distributions of these three atmospheric gases at both equinox and solstice, with emphasis on the winter enhancement of atomic oxygen in the lower thermosphere. Comparison of the results with measurements taken by the ESRO-4 mass spectrometer indicates that the distribution of atomic oxygen can be generally understood as being a result of global transport by winds. Oxygen chemistry, not included in the calculations to date, could modify these results, but, because of the time scales involved, would not change the basic conclusions.

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I. INTRODUCTION

During the first year of this contract, calculations dealing with the global distributions of the minor gases He and Ar were carried out. The calculations made use of a numerical model of the thermosphere in which the influence of a background gas on the dynamics of a minor gas is considered. The model covers the range 90-500 km, and the background gas density, mean molecular weight and temperature were taken from the CIRA (1972) empirical model. Wind fields in the background and minor gases are calculated using the equations of conservation of momentum, including the effects of anisotropic ion drag, viscosity and the Coriolis force, as well as pressure gradients derived from the density and temperature gradients.

Although the previously described model calculations reproduced the general observed features of the "winter helium bulge," including the decrease of its amplitude with increasing solar activity and the latitudes and local times of the helium density extrema, quantitative comparison of the results of the model calculations with data taken by satellite-borne mass spectrometers indicated that the computed amplitude of the winter helium bulge was somewhat underestimated. For example, for $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$ and $K_p = 0$, our model predicted a helium bulge ratio (ratio of maximum to minimum helium density at a given altitude) of ~ 28 at 275 km altitude, as opposed to a value of ~ 42 measured by the ESRO-4 satellite (Keating et al., 1976; von Zahn et al., 1977). Similarly, for $F_{10.7} = 140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$, the theoretical model predicted a helium bulge ratio of ~ 12 at 400 km, whereas the OGO-6 mass spectrometer gave a value ~ 20 (Hedin et al., 1974).

Since the primary mechanism responsible for the winter helium bulge is transport of helium from the summer to the winter hemisphere by global-scale winds in the background gas, the underestimate of the amplitude of the winter helium bulge is attributed to an underestimate of the speed of the meridional wind flowing from the summer to the winter hemisphere. This wind speed would be increased if the latitudes at which the extrema of the background gas pressure occur were larger than those given by the CIRA (1972) model. The CIRA (1972) model places the pressure maximum at the subsolar latitude (23.5° under summer solstice conditions) and the pressure minimum at the anti-subsolar latitude. That these are the correct locations for the pressure extrema is far from clear. Data taken by the satellite-borne mass spectrometers mentioned earlier indicate that the solstitial temperature extrema occur at considerably higher latitudes; the locations of the density extrema depend on the molecular weight of the gas in question, and the locations of the total pressure extrema generally differ from those given by the CIRA model.

Recently, Jacchia (1977) has presented a new empirical model of thermospheric temperature, density and composition. This model includes changes in composition observed by the mass spectrometers on board the OGO-6 and ESRO-4 satellites, while keeping the total density profiles anchored to satellite drag data. The model has a formulation basically similar to that of CIRA (1972), but its detailed model predictions are quite different in several respects. Of most relevance here is the fact that, even under $K_p = 0$ conditions, the exospheric temperature extrema at solstice occur at $\sim \pm 45^\circ$ latitude, considerably poleward of

their positions in CIRA (1972). Thus, even though the total density extrema occur at latitudes near the subsolar and anti-subsolar latitudes, the total pressure extrema occur somewhat poleward of the corresponding positions in CIRA (1972). Thus, one should expect that use of the Jacchia (1977) model, in place of the CIRA model, to specify the temperature and background gas pressure would lead to an increase in the helium bulge ratio, all other factors remaining unchanged.

This feature of the Jacchia (1977) model has a further relevant effect. Exospheric flow of helium tends to reduce the amplitude of the winter helium bulge. The amount of exospheric flow depends on the value of the quantity $Q = \nabla_{\perp}^2 (nT^{5/2})$ evaluated at the base of the exosphere; here n is the helium number density, T is the temperature, and $\nabla_{\perp}^2$ is the horizontal Laplacian operator. Since the maximum of n occurs at high latitudes in the hemisphere in which T takes on its minimum value, Q is reduced by increasing the latitudes at which the extrema of T occur. Thus, use of the Jacchia (1977) model is expected to lead to an increase in the predicted amplitude of the winter helium bulge, both because it increases the flow of helium from the summer to the winter hemisphere in the thermosphere, and because it decreases the return flow of helium in the exosphere.

Section II of this Addendum describes an investigation of the extent to which use of the Jacchia (1977) model can improve the agreement between the predictions of our theoretical model and measurements of the amplitude of the winter helium bulge measured by the ESRO-4 and OGO-6 mass spectrometers.

In addition to the inert gases, which are minor constituents of the thermosphere at all altitudes below ~ 500 km, atomic oxygen is a minor species in the lower thermosphere (below ~ 140 km). That the distribution of atomic oxygen in the thermosphere is sensitive to phenomena other than photochemical processes and hydrostatic equilibrium was first suggested by King (1964) and Johnson (1964). They discussed the importance of horizontal transport of atomic oxygen from the summer to the winter hemisphere and how it can explain the observed decrease in the fraction of molecular ions in the F-region in winter. Several sources of data have confirmed this conclusion. Measurements using the satellites Explorers 19 and 39 near opposite poles at ~ 1000 km altitude were used by Keating et al. (1971) to infer that the maximum O concentration near 120 km altitude occurs at low latitudes in the winter hemisphere. They pointed out that this winter enhancement of O can result from the same type of meridional flow into the winter hemisphere that produces the winter helium bulge (Keating and Prior, 1967, 1968). The fact that, at higher thermospheric altitudes, the atomic oxygen maximum occurs in the summer hemisphere was attributed to the fact that temperatures in the summer hemisphere exceed those in the winter. Barlier et al. (1971) and Alcayde et al. (1974) used incoherent scatter radar measurements and satellite drag data to infer a winter maximum of atomic oxygen in the lower thermosphere. Donahue et al. (1973) gave an exhaustive discussion of OGO-6 observations of the 5577 nightglow and their implications for the atomic oxygen distribution in the 80-120 km altitude range. They demonstrated that, assuming that latitudinal variations in the eddy diffusion coefficient

are not large enough to be dominant, the large latitudinal variations in the density of O requires meridional flows of 10-50 m/sec at the 100 km level. Offermann (1974) presented a collection of density and composition data taken by instruments on various rockets; he showed that in the 120-200 km altitude range, the minimum O density occurs ~ 30 days after summer solstice. He also demonstrated that at 150 km, the seasonal variation of the $n(O)/n(O_2)$ ratio is ~ 2 and is thus larger than variations correlated with solar flux, geomagnetic activity or local time. More recently, mass spectrometer data have been used to describe the global variation of atomic oxygen concentrations. (See for example, Hedin et al., 1973; Newton et al., 1975; Keating et al., 1976; Mauersberger et al., 1976; von Zahn et al., 1977). These data have been incorporated into the Mass-Spectrometer Incoherent Scatter Model by Hedin et al. (1977).

Theoretical studies dealing with the global distribution of atomic oxygen include the seasonal model of Mayr and Volland (1972), in which both helium and atomic oxygen winter bulges were found to be produced in the lower thermosphere by circulation. At higher altitudes, thermal expansion was shown to be more important than circulation for O, leading to a maximum of O in the summer hemisphere above ~ 440 km altitude. Johnson and Gottlieb (1973) and Johnson (1973) demonstrated that a meridional wind system that is required from thermal budget considerations is adequate to transport the needed quantity of O from the summer to the winter hemisphere. Johnson concluded that, although the same transport processes act on O as on He, the effect on O should be

smaller than that on He because the scale height of O is less than a factor of 2 greater than the average atmospheric scale height in the lower thermosphere. Finally, Mayr and Harris (1977) presented a theoretical model of the diurnal variations in thermospheric temperature, composition and winds. Using perturbation theory, they showed that thermospheric winds have a substantial effect on atomic oxygen below 200 km. They tend to shift the diurnal maximum of $n(O)$ in the lower thermosphere to times earlier than would occur under the action of hydrostatic equilibrium alone. A gradual phase transition occurs, with maximum $n(O)$ occurring at ~ 6 LT at 150 km and at ~ 14 LT at 300 km. Chemistry was shown to be of secondary importance in determining the diurnal variations of $n(O)$.

As part of our investigations this year, a study of the dynamics of atomic oxygen has been carried out. Because atomic oxygen becomes the major thermospheric constituent above ~ 150 km, the numerical model used in the study of He and Ar could not be used to study the distribution of atomic oxygen. An interactive three-component model, whose development was begun under funding by Aerospace Corporate Programs for Research and Investigation, was used to investigate the dynamics of N_2 , O_2 and O. The mathematical formulation and implementation of this model are described in Sections III and IV.

II. USE OF THE JACCHIA (1977) MODEL IN DETERMINING THE GLOBAL DISTRIBUTION OF THERMOSPHERIC HELIUM

The complete formulation of the three-dimensional theoretical model was described in the original report (Straus et al., 1977). The only modification made for the present calculations involved using the Jacchia (1977) model in place of the CIRA (1972) model for specifying the temperature and background gas pressure in the 90-500 km altitude range. Calculations were carried out for June solstice conditions with values of $F_{10.7} = 92$ and $140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$; these values allow direct comparison to be made with the data taken by the ESRO-4 and OGO-6 mass spectrometers. In order to isolate the effects of changes in the background gas distribution, all calculations were carried out for $K_p = 0$ and eddy diffusion coefficient $K = 6 \times 10^6 \text{ cm}^2/\text{sec}$. In describing the results of these calculations, we shall refer to the use of CIRA (1972) as "Model 1" and the use of Jacchia (1977) as "Model 2".

Figure 1 shows the zonally averaged meridional velocity $\bar{v}_\theta$ across the equator for Models 1 and 2 for the two values of $F_{10.7}$. (Positive v_θ corresponds to southward flow.) In all cases, throughout most of the thermosphere the zonally averaged motion is directed toward the winter hemisphere; a small region of reversed flow occurs at low thermospheric altitude. Generally, $\bar{v}_\theta$ increases with $F_{10.7}$; because of an increase in the ion density with $F_{10.7}$, $\bar{v}_\theta$ does not increase with $F_{10.7}$ as rapidly as do the pressure gradients. For both values of $F_{10.7}$, the values of $\bar{v}_\theta$ calculated using Model 2 exceed those from Model 1; however, the increase is no more than $\sim 10 \text{ m/sec}$, and values of this magnitude occur only in the upper thermosphere, where wind-induced departures from hydrostatic equilibrium do not occur.

Figure 2 shows contours of constant values of $\log_{10} (\rho_{\text{He}}, \text{g/cm}^3)$ at 275 km at June solstice for $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$ calculated using both Models 1 and 2. Both figures show isopycnics which are strikingly similar in their general features and shapes to those generated by von Zahn et al. (1977) from data taken by the ESRO-4 mass spectrometer. Comparison of these two figures and a more detailed tabulation of the results indicate the following:

- 1) Model 2 produces a larger ratio of maximum to minimum He density than does Model 1, although the global average He density is essentially unchanged.
- 2) Model 2 produces helium density extrema at higher latitudes than does Model 1.
- 3) Model 2 produces helium density extrema at very slightly later local times than does Model 1.

All of these results are to be expected. The helium bulge ratio and the latitudes of the helium density extrema increase because of changes in the meridional flow. The local times of the helium density extrema increase because the Jacchia (1977) model places the temperature maximum at ~ 17 hours local time (and total density maximum at 1415 LT), whereas the temperature maximum in the CIRA (1972) model occurs at 1415 LT, along with the total density maximum. Thus, the total pressure extrema occur at slightly later local times in the Jacchia (1977) model than in the CIRA (1972) model.

Figure 3 compares the calculated vertical distribution of the helium bulge ratio with those given by the ESRO-4 empirical model for $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$ and the OGO-6 empirical model for

$F_{10.7} = 140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$. In each of the curves representing theoretical results, wind-induced departures from hydrostatic equilibrium cause the helium bulge ratio to rise rapidly from its value 1 at 90 km to a maximum near 250 km. Above that altitude, hydrostatic equilibrium prevails because molecular diffusion effects dominate large-scale transport processes, and the bulge ratio decreases at a rate dependent on the temperature. Thus, the behavior below ~ 250 km is that which the empirical models attempt to represent by spatially-varying lower boundary conditions. For a fixed value of $F_{10.7}$, the bulge ratio calculated using Model 2 exceeds that resulting from Model 1 at all altitudes and leads to substantially better agreement with the empirical models. Comparison of the OGO-6 model for $F_{10.7} = 140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$ with the theoretical calculations indicates that Model 2 yields a helium bulge ratio within $\sim 15\%$ of the OGO-6 value in the 400-450 km altitude range, where the OGO-6 data were taken. Similarly, the predictions of Model 2 are within $\sim 15\%$ of the ESRO-4 model for $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$ at 275 km.

In summary, we have shown that use of the Jacchia (1977) model to specify the temperature and background gas pressure distributions in a three-dimensional dynamical model of thermospheric helium leads to better agreement with observational data than does use of CIRA (1972) (Straus et al., 1977). The calculated increases in the amplitude of the winter helium bulge and the latitudes at which the helium density extrema occur are primarily due to increased meridional transport of helium from the summer to the winter hemisphere by large-scale winds. However, the fact that the winter helium bulge amplitude decreases with

increasing solar activity is not due to a decrease in wind speed with solar activity, but rather to the increased effectiveness of exospheric transport, which carries helium back to the summer hemisphere. It is also worthy of note that the amplitude of the winter helium bulge appears to be an extremely sensitive function of the background gas pressure distribution, so the observed substantial variations in the helium distribution with geomagnetic activity are quite understandable.

III. THE THREE-COMPONENT MODEL

In order to study the dynamics of the thermosphere, the model treats the three main gases N_2 , O_2 , and O , coupled together by collisional and chemical processes. The conservation of mass and momentum equations are solved in a spherical shell with lower and upper boundaries at 90 and 500 km, respectively. As in our earlier work, the temperature field has been taken from CIRA (1972). Under steady-state conditions, the equations of mass and momentum conservation of the i^{th} species in a spherical (r, θ, ϕ) coordinate system are:

$$\Omega \partial \rho_i / \partial \phi + \nabla \cdot (\rho_i \mathbf{v}_i) = S_i - L_i \quad (1)$$

$$\Omega (\partial \mathbf{v}_i / \partial \phi) + \mathbf{v}_i \cdot \nabla \mathbf{v}_i + 2 \mathbf{\Omega} \times \mathbf{v}_i =$$

$$\left(\bar{D}_i + K \frac{\bar{m}}{m_i} \right) \mathbf{g} / \left(\bar{D}_i + K \right)$$

$$- (1/\rho_i) \nabla p_i + (\mu_i/\rho_i) \nabla^2 \mathbf{v}_i - \nu_{iI} (\mathbf{v}_i - \mathbf{v}_I)$$

$$- \sum_{j \neq i} \nu_{ij} (\mathbf{v}_i - \mathbf{v}_j) \quad (2)$$

Here, $\mathbf{\Omega}$ is the angular rotation rate of the earth, ρ is the density, $\mathbf{v}$ is the velocity vector, $\mathbf{g}$ is the acceleration of gravity, p is the pressure ($p_i = \rho_i kT/m_i$, where k is Boltzmann's constant, T is the temperature and m_i is the gas molecular weight), μ is the viscosity,

ν_{iI} is the neutral-ion collision frequency ($\nu_{iI} = 2.6 \times 10^{-9} M^{-1/2} n_i$, where M is the gas molecular weight in AMU and n_i is the ion number density, taken from the empirical model of Ching and Chiu (1973)) $\underline{v}_I$ is the ion velocity, taken to be equal to $(\bar{\underline{v}} \cdot \hat{b}) \hat{b}$, where $\bar{\underline{v}}$ is the mass-average neutral velocity and $\hat{b}$ is the unit vector in the direction of the geomagnetic field.

The last term in equation 2 represents momentum transfer due to collisions between neutral species. We use

$$\nu_{ij} = kT n_j / m_i D_{ij} N, \quad (3)$$

where $N = \sum_k n_k$ and D_{ij} is the binary diffusion coefficient (Banks and Kockarts, 1973). The gravity term allows a transition from complete mixing in the lower thermosphere ($K \gg \bar{D}_i$) to diffusive equilibrium in the upper thermosphere ($\bar{D}_i \gg K$). Here,

$$\bar{D}_i = \left\{ \sum_{j \neq i} n_j / N D_{ij} \right\}^{-1}.$$

All of the calculations to be described here were carried out with a single value of $K = 6 \times 10^6 \text{ cm}^2/\text{sec}$. This circumstance is primarily due to the expense involved in the computations. Furthermore, as shown in our earlier work, a change in the globally uniform value of K does not have an important effect on the global variability of the thermospheric He density. Since the gases treated here have molecular weights much closer to the average than does helium, the results should be even less sensitive to the value of K used, as long as it lies in the range $10^6 - 10^7 \text{ cm}^2/\text{sec}$.

The terms S_i and L_i in (1) represent source and loss terms due to chemical processes (photodissociation, photoionization, recombination, etc.) The only processes of possible importance in the present model involve oxygen chemistry. Atomic oxygen is produced by photodissociation of O_2 in the lowest part of the thermosphere by solar radiation with wavelength $\lambda < 2424\text{\AA}$. Because the recombination of O to form O_2 is a three-body reaction, photochemical equilibrium is accomplished by eddy transport of atomic oxygen from its point of formation downward into the mesosphere, where recombination occurs. This is an extremely complex process, and only investigations using one-dimensional photochemical models have been carried out. Understanding of this process has not progressed to a point where oxygen chemistry can be included in the present study. It is fortunate that the inclusion of oxygen chemistry is not crucial in understanding the global distribution of O in the thermosphere. The time required for photochemical equilibrium to occur at 100 km altitude is on the order of

1 month and increases with altitude (Banks and Kockarts, 1973). Thus dynamical processes with time scales less than this will dominate the photochemical processes. This is certainly the case for diurnal variations. As will be seen, the winter enhancement of atomic oxygen in the lower thermosphere can be understood as being a manifestation of meridional winds, whose time scale for transport from one hemisphere to the other is on the order of 1-4 days.

Equations 1-3 are solved simultaneously for the 3 gases using the spectral method described by Creekmore et al. (1975). Because of the large size of the system of equations involved, special procedures for solving the coupled nonlinear algebraic equations were devised, tested and used extensively in this investigation.

The boundary conditions employed were that, at 90 km, all velocities vanish and the densities of the 3 gases are those given in CIRA (1972). At 500 km, the horizontal velocities, $\tilde{v}_i$ are assumed to have no vertical variation (i.e., $\partial \tilde{v}_i / \partial z = 0$ at 500 km).

IV. RESULTS AND DISCUSSION

Computations as described in the previous section were carried out for equinox conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$ and for solstice conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$ and $140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$. The smaller value of $F_{10.7}$ was chosen to allow direct comparison with the ESRO-4 measurements, whereas the larger value corresponds to those of OGO-6. The horizontal and vertical winds thus calculated are similar to those discussed in our first report (Straus et al., 1977). In this report, we shall describe the density distributions of the three major gases in some detail, with emphasis on wind-induced departures from hydrostatic equilibrium.

Figures 4-9 show contours of the natural logarithm of the density (gm/cm^3) of the atmospheric constituents N_2 , O_2 and O at several altitudes under spring equinox conditions for $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$. Figures 4-6 show results for hydrostatic conditions, whereas Figures 7-9 illustrate complete calculations, including the effect of wind-induced diffusion. Comparison of corresponding figures for the hydrostatic and non-hydrostatic calculation shows important effects in the lower thermosphere. Molecular oxygen and nitrogen show some departure from hydrostatic equilibrium below $\sim 200 \text{ km}$ altitude, the departure being larger for O_2 than for N_2 . Since O_2 has a molecular weight larger than the average (which is close to that of N_2 in the lower thermosphere) this is to be expected. The effects of winds are large enough to move the position of maximum $n(\text{O}_2)$ and $n(\text{N}_2)$ away from the equator in the lower thermosphere and to generally change the shapes of the contours, although the mean density at a given altitude is

essentially unchanged. Furthermore, the local times of maximum density (phase) of N_2 and O_2 are later in the non-hydrostatic cases than under hydrostatic conditions. Above ~ 200 km, the effects of vertical motions on the N_2 and O_2 densities become negligible, and hydrostatic equilibrium prevails.

Figures 6 and 9 show that departures from hydrostatic equilibrium are more substantial in the case of atomic oxygen than for N_2 or O_2 . Below ~ 200 km, the atomic oxygen density has a pronounced maximum at ~ 13 hours local time on the equator and strong minima at high latitudes in both hemispheres. The region from 200-300 km displays a transition to hydrostatic equilibrium, with the effects of non-hydrostaticity at lower altitudes being still visible at 470 km, especially in the asymmetry of the diurnal variation.

Data relevant to global variation of the atomic oxygen density at equinox have been collected by several satellite-borne mass spectrometers. Hedin et al. (1977) have used data from several satellites to generate the Mass Spectrometer-Incoherent Scatter (MSIS) Model. Comparison of this model which calculated results presented here for atomic oxygen shows reasonably good agreement, especially in light of the uncertainties in several relevant input parameters, lower spatial resolution in the theoretical model, and extrapolations in the MSIS model to altitudes below those at which data were taken. Due to the neglect of oxygen chemistry, the global mean $n(O)$ is generally lower in the theoretical model than in MSIS. However, the global variations of $n(O)$ at a fixed altitude are similar in both magnitude and geographical

distribution. For example, at 120 km altitude, both the theoretical model and MSIS show minimum $n(O)$ at high latitudes in both hemispheres and a broad region of larger $n(O)$ near, and centered on, the equator. At 140 km, the MSIS model shows a 50% variation in $n(O)$, whereas the theoretical model shows a 40% variation. Departures from hydrostatic equilibrium are clear in MSIS at all altitudes below ~ 400 km, with a broad transition region in the 200-400 km altitude range.

Figures 10-15 compare the hydrostatic and non-hydrostatic distributions of N_2 , O_2 and O at several altitudes for June solstice conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$. As in the equinox calculations, the N_2 and O_2 distributions show some effects of wind-induced departures from hydrostatic equilibrium. In the lower thermosphere, winds drive the positions of the extrema of $n(N_2)$ and $n(O_2)$ to higher latitudes and somewhat later local times than those calculated under the hydrostatic assumption. This behavior is similar to that described by Straus (1977) for thermospheric argon. Furthermore, the amplitudes of the global variations of $n(N_2)$ and $n(O_2)$ are increased in the full calculation, relative to the hydrostatic calculation. For example, at 120 km altitude, the ratio of maximum $n(N_2)$ to minimum $n(N_2)$, to which we shall refer as $R(N_2)$, is increased from ~ 1.17 to ~ 1.30 ; similarly, $R(O_2)$ at 120 km is increased from ~ 1.18 to ~ 1.42 . The global mean values of $n(N_2)$ and $n(O_2)$ are essentially unchanged. At 185 km, the corresponding values for $R(N_2)$ are 1.90 and 2.30, and those for $R(O_2)$ are 2.04 and 2.79.

Above ~ 200 km, molecular diffusion effects become larger, and the N_2 and O_2 distributions become more nearly hydrostatic. The contours shown in panels d, e and f of Figures 10, 11, 13 and 14 show that hydrostatic equilibrium clearly holds above this altitude. Furthermore, the scale heights of N_2 and O_2 are small enough that these species are quite sensitive to global temperature variations in the upper thermosphere. Thus, a transition region exists in the 200-300 km altitude range, above which the global distributions of $n(N_2)$ and $n(O_2)$ strongly resemble that of the temperature.

Atomic oxygen is greatly affected by transport by global-scale winds, leading to a winter bulge of O in the lower thermosphere. Comparison of Figures 12 and 15 indicates that winds drive atomic oxygen from the summer hemisphere, where the $n(O)$ maximum occurs under hydrostatic conditions, to the winter hemisphere. The calculations indicate that this winter enhancement of O exists even at the lowest level in the model, 91 km, where the maximum $n(O)$ occurs at -30° latitude, 8 hours local time. The global maximum $n(O)$ at June solstice at 120 km altitude occurs at ~ 10 hours local time, -30° latitude. With increasing altitude, the maximum value of $n(O)$ at a given altitude moves towards the summer hemisphere and later local time. It reaches the equator at ~ 300 km altitude, where the local time of maximum $n(O)$ is ~ 13 hours. The slow transition with altitude of the location of maximum $n(O)$ is consistent with its relatively long scale height; atomic oxygen is less sensitive to global temperature variations than are N_2 and O_2 . (In the case

of the very light gas He, the transition effectively does not occur at all, and the maximum $n(\text{He})$ occurs at very high winter latitudes in the early morning hours.) The amplitude of the winter enhancement of O, measured by $R(\text{O})$, is shown in Table 1 as a function of altitude, for calculations with $F_{10.7} = 92$ and $140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$. (The contour plots for the latter value of $F_{10.7}$ are given in Figures 16-18.) This table indicates that $R(\text{O})$ below ~ 200 km increases slightly with $F_{10.7}$, but the increase is not significant. At higher altitudes, the ratio is less meaningful as a measure of the winter atomic oxygen bulge, since the extrema of $n(\text{O})$ occur near the equator, and the winter bulge of O does not really exist.

The results of these calculations can be compared directly with data taken by satellite-borne mass spectrometers. Von Zahn et al. (1977) give contour plots of the global distribution of N_2 and O at 275 km altitude under June solstice conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$. Comparison of these figures with figures 13d and 15d shows very good agreement. For N_2 , the local times of the extrema of $n(\text{N}_2)$ are faithfully predicted by the theoretical calculations. The latitudes of the extrema are somewhat closer to the equator in the theoretical model than in the empirical model; because N_2 is sensitive to the temperature distribution, this disagreement is probably due to the position of the temperature extrema in the CIRA (1972) model. In the case of O, the agreement is quite excellent, considering that the small-scale features shown in the figure of von Zahn et al. cannot be resolved by the theoretical model. The local

TABLE 1

Ratio of Global Maximum to Minimum $n(O)$, $R(O)$

<u>Altitude (km)</u>	<u>$R(O)$, $F_{10.7} = 92$</u>	<u>$R(O)$, $F_{10.7} = 140$</u>
105	1.22	1.22
119	1.41	1.46
143	1.64	1.73
185	1.83	1.89
260	1.91	1.73

times of the extrema of $n(O)$ are well represented, and the latitudes of the extrema of $n(O)$ agree well. The value of $R(O)$ is ~ 2.0 in both the theoretical and empirical models.

Similar agreement exists between the theoretical model and the OGO-6 empirical model (Hedin et al., 1974). Hedin et al. show contours of $n(O)$ at 450 km under June solstice conditions with $F_{10.7} = 140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$. Comparison of the plot with Figure 18f (470 km) shows that the theoretical model predicts the correct location of the $n(O)$ extrema near the equator. Furthermore, the values of $R(O)$ are very nearly equal, 2.7 for the OGO-6 model and 2.9 for the theoretical model.

As mentioned earlier, the MSIS empirical model (Hedin et al., 1977) combines density data taken by several satellite-borne mass spectrometers. The general features of the distribution of atomic oxygen in the MSIS model are similar to those of the ESRO-4 and OGO-6 models. The MSIS model, like our theoretical model, shows that the winter enhancement of atomic oxygen extends to very low thermospheric altitudes. The maximum $n(O)$ occurs at middle latitudes in the winter hemisphere, while the minimum $n(O)$ occurs at high summer latitudes. In the 200-400 km region, the position of maximum $n(O)$ shifts towards the summer hemisphere, in response to the high temperature there. Finally, as in the theoretical model, $R(O)$ is relatively insensitive to $F_{10.7}$, increasing only slightly as $F_{10.7}$ is increased from 90 to $150 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$. (The global average value of $n(O)$, of course, increases with $F_{10.7}$.)

Comparisons of the results of the theoretical model with data that have not been included in global empirical models may also be made. There is a large amount of this type of data from both rockets and satellites, but most of it deals with absolute measurement of composition or ratios of the density of various species at a particular geographical locale, time of day, day of year, etc. The sources of data directly relevant to the present investigation, i.e., the seasonal variation of the atomic oxygen distribution, are, in fact, quite limited. Offermann (1974), in a discussion of composition data obtained from rocket experiments in the altitude range 120-200 km, finds that there is a strong winter enhancement, with $R(O) \sim 1.9$ at 200 km. This is in good agreement with the result of the theoretical model, as given in Table 1. Finally, Mauersberger et al. (1976) have discussed data taken at high northern latitudes in the winter and summer of 1974 by the open source neutral mass spectrometer on the AE-C satellite. They indicate that the ratio of $n(O)$ at $\sim 60^\circ$ latitude in early February to that in late June is ~ 1.5 at 300 km, eventually crossing 1.0 at ~ 375 km. The results of the theoretical model are in reasonably good agreement with these findings.

V. CONCLUSIONS

In this report, we have described the continuation of theoretical studies of minor constituents in the thermosphere. Use of the Jacchia (1977) model for specifying the background gas pressure in our two-component model dealing with the distribution of thermospheric helium leads to considerably better agreement of the model predictions with observational data than we had obtained in previous calculations using CIRA (1972). A new model of N_2 , O_2 and O was applied to a study of the global distributions of these three gases, with particular emphasis on the seasonal variation of atomic oxygen. The model correctly predicts a winter enhancement of atomic oxygen in the lower thermosphere, with the position of maximum $n(O)$ gradually shifting towards the summer hemisphere in the thermopause region. Comparison of the model results with observational data shows generally good quantitative agreement, especially in light of the relatively low spatial resolution of the model.

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FIGURE CAPTIONS

- Figure 1. Zonally averaged meridional wind speed at the equator calculated for $F_{10.7} = 92$ and $140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$ using Models 1 and 2.
- Figure 2. Contours of constant values of $\log_{10} (\rho_{\text{He}}, \text{ g/cm}^3)$ at 275 km altitude at June solstice for $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.
- a. Model 1
 - b. Model 2
- Figure 3. Comparison of the He bulge ratio as a function of altitude as predicted by Models 1 and 2 for two values of $F_{10.7}$ with the empirical models based on data from the ESRO-4 and OGO-6 mass spectrometers.
- Figure 4. Contours of $\ln (\rho_{\text{N}_2}, \text{ g/cm}^3)$ at spring equinox for hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.
- a. 119 km
 - b. 143 km
 - c. 185 km
 - d. 260 km
 - e. 365 km
 - f. 470 km

Figure 5. Contours of $\ln(\rho_{\text{O}_2}, \text{g/cm}^3)$ at spring equinox for hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 6. Contours of $\ln(\rho_{\text{O}}, \text{g/cm}^3)$ at spring equinox for hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 7. Contours of $\ln(\rho_{\text{N}_2}, \text{g/cm}^3)$ at spring equinox for non-hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 8. Contours of $\ln(\rho_{O_2}, \text{g/cm}^3)$ at spring equinox for non-hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 9. Contours of $\ln(\rho_0, \text{g/cm}^3)$ at June solstice for hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 10. Contours of $\ln(\rho_{N_2}, \text{g/cm}^3)$ at June solstice for hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 11. Contours of $\ln(\rho_{\text{O}_2}, \text{g/cm}^3)$ at June solstice for hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 12. Contours of $\ln(\rho_{\text{O}}, \text{g/cm}^3)$ at June solstice for hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 13. Contours of $\ln(\rho_{\text{N}_2}, \text{g/cm}^3)$ at June solstice for non-hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 14. Contours of $\ln(\rho_{\text{O}_2}, \text{g/cm}^3)$ at June solstice for non-hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 15. Contours of $\ln(\rho_{\text{O}}, \text{g/cm}^3)$ at June solstice for non-hydrostatic conditions with $F_{10.7} = 92 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 16. Contours of $\ln(\rho_{\text{N}_2}, \text{g/cm}^3)$ at June solstice for non-hydrostatic conditions with $F_{10.7} = 140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 17. Contours of $\ln(\rho_{\text{O}_2}, \text{g/cm}^3)$ at June solstice for non-hydrostatic conditions with $F_{10.7} = 140 \times 10^{-22} \text{W/m}^2 \text{Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

Figure 18. Contours of $\ln(\rho_{\text{O}}, \text{g/cm}^3)$ at June solstice for non-hydrostatic conditions with $F_{10.7} = 140 \times 10^{-22} \text{W/m}^2 \text{Hz}$.

- a. 119 km
- b. 143 km
- c. 185 km
- d. 260 km
- e. 365 km
- f. 470 km

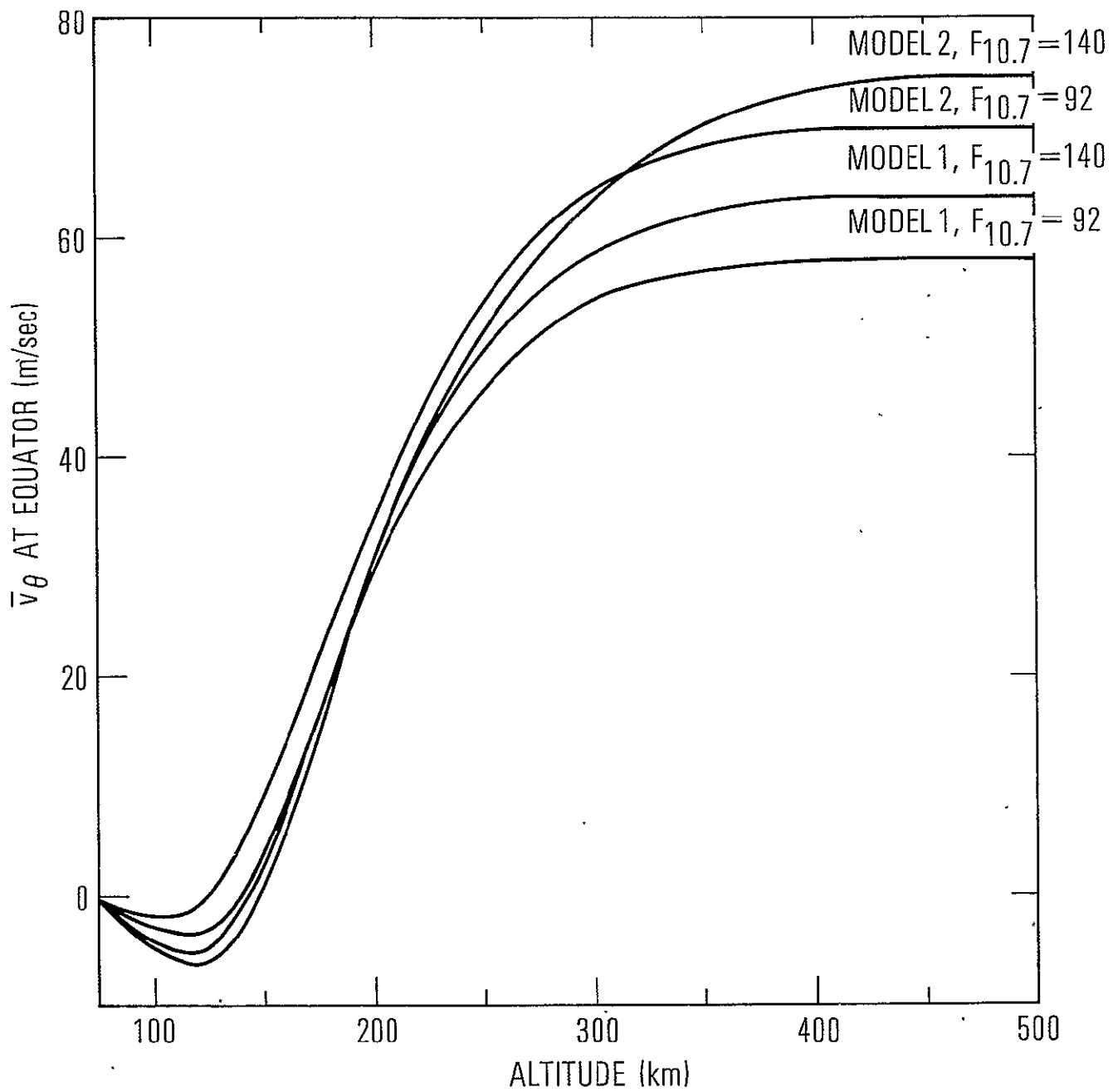


Fig
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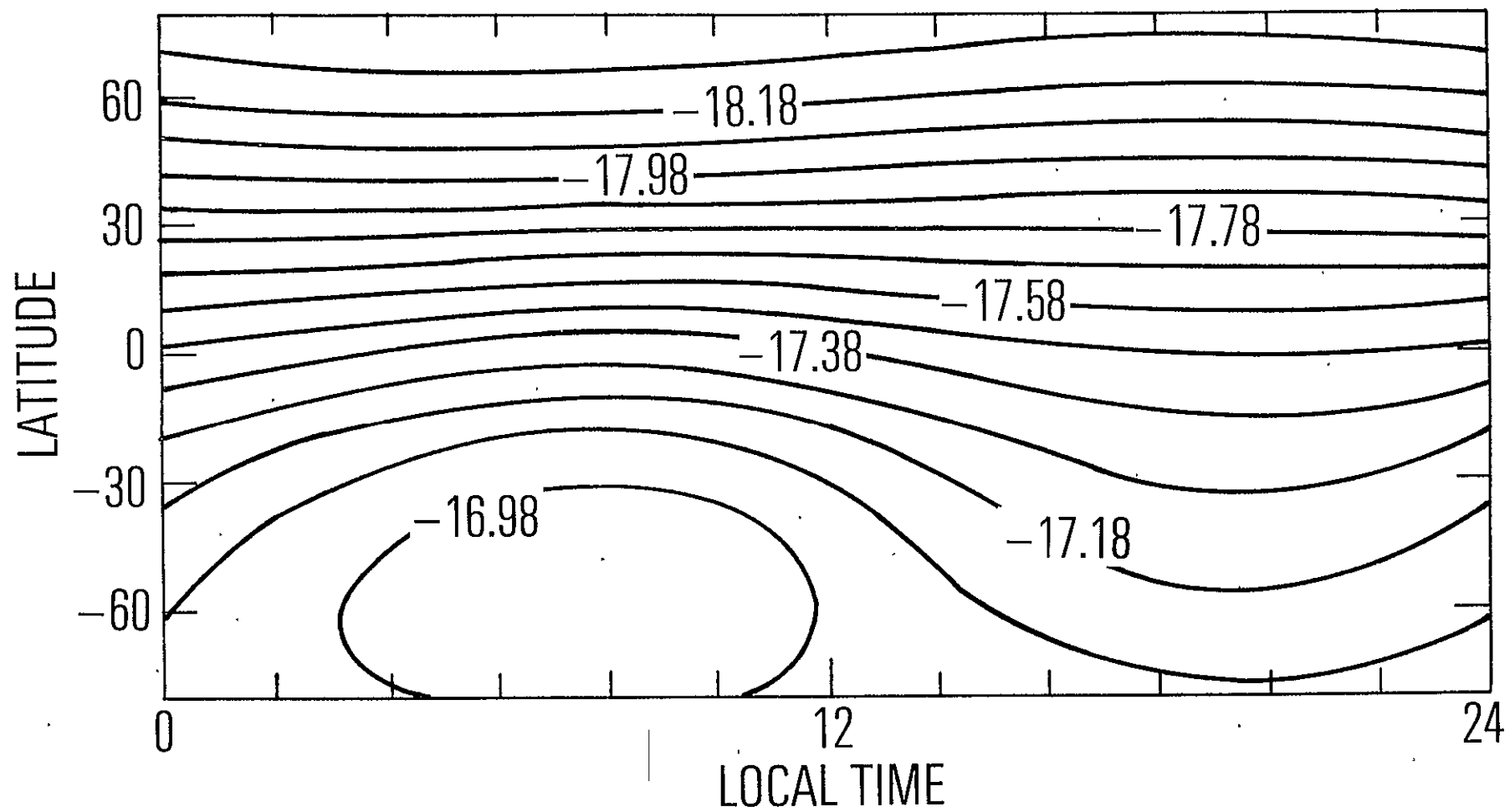
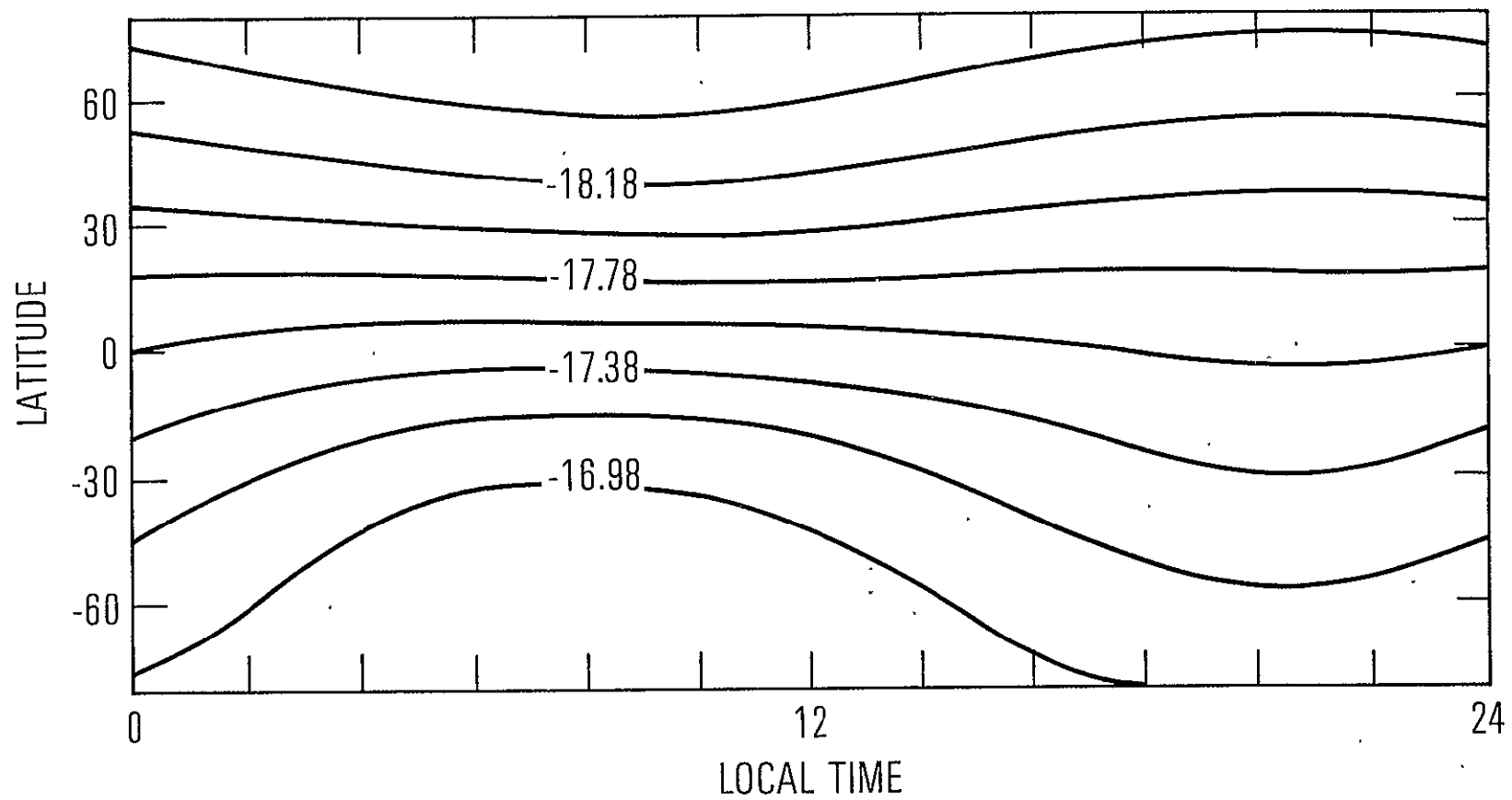


Fig.
2a



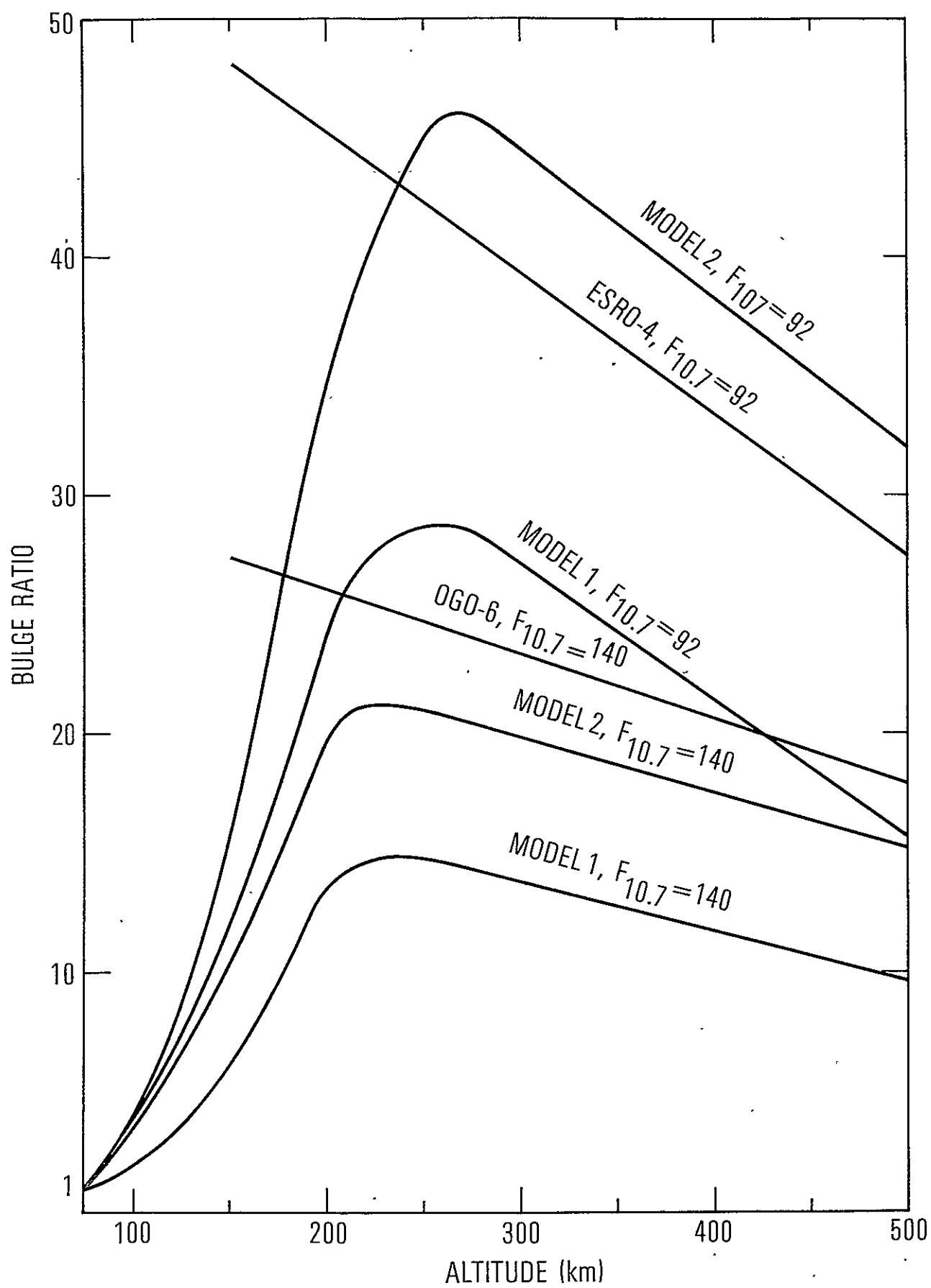


Fig
3

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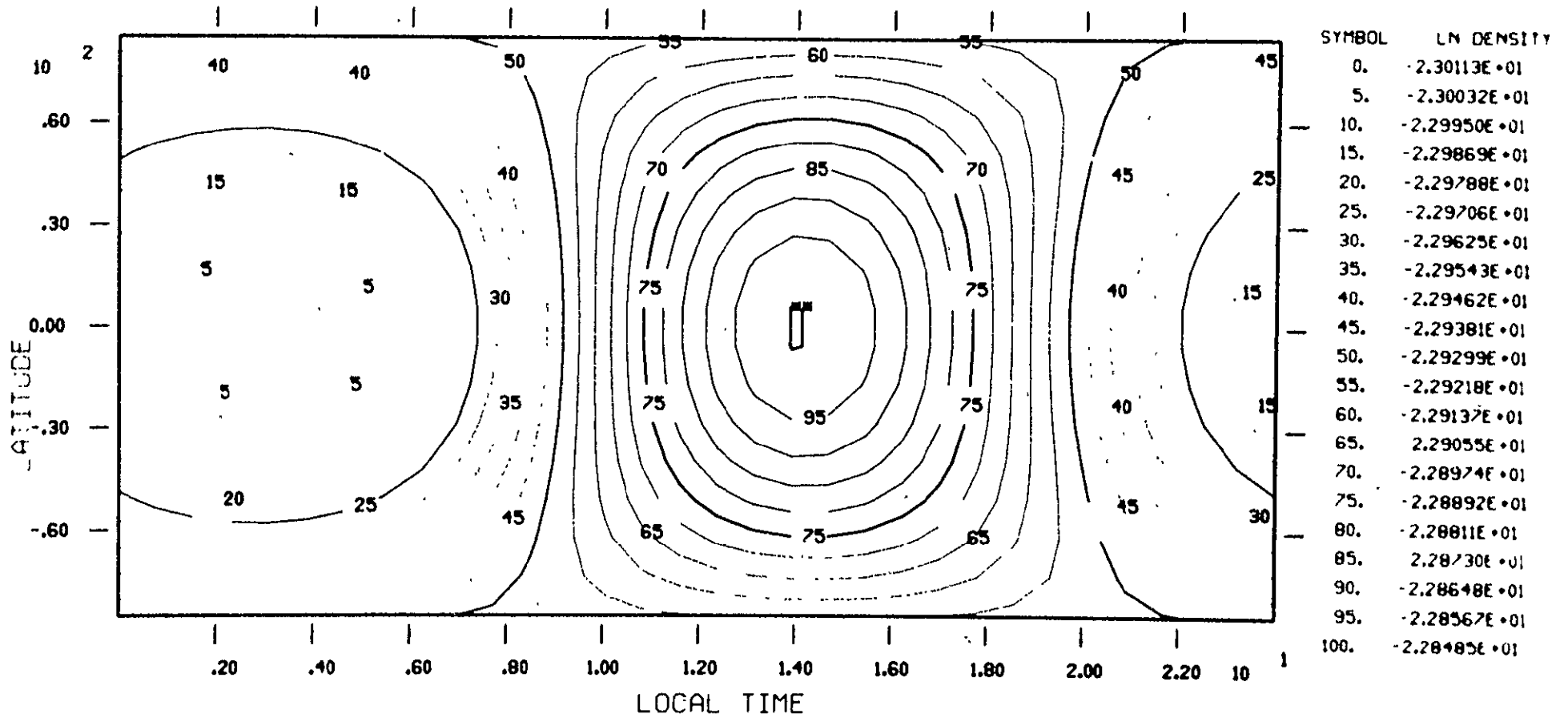
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DAY 80.

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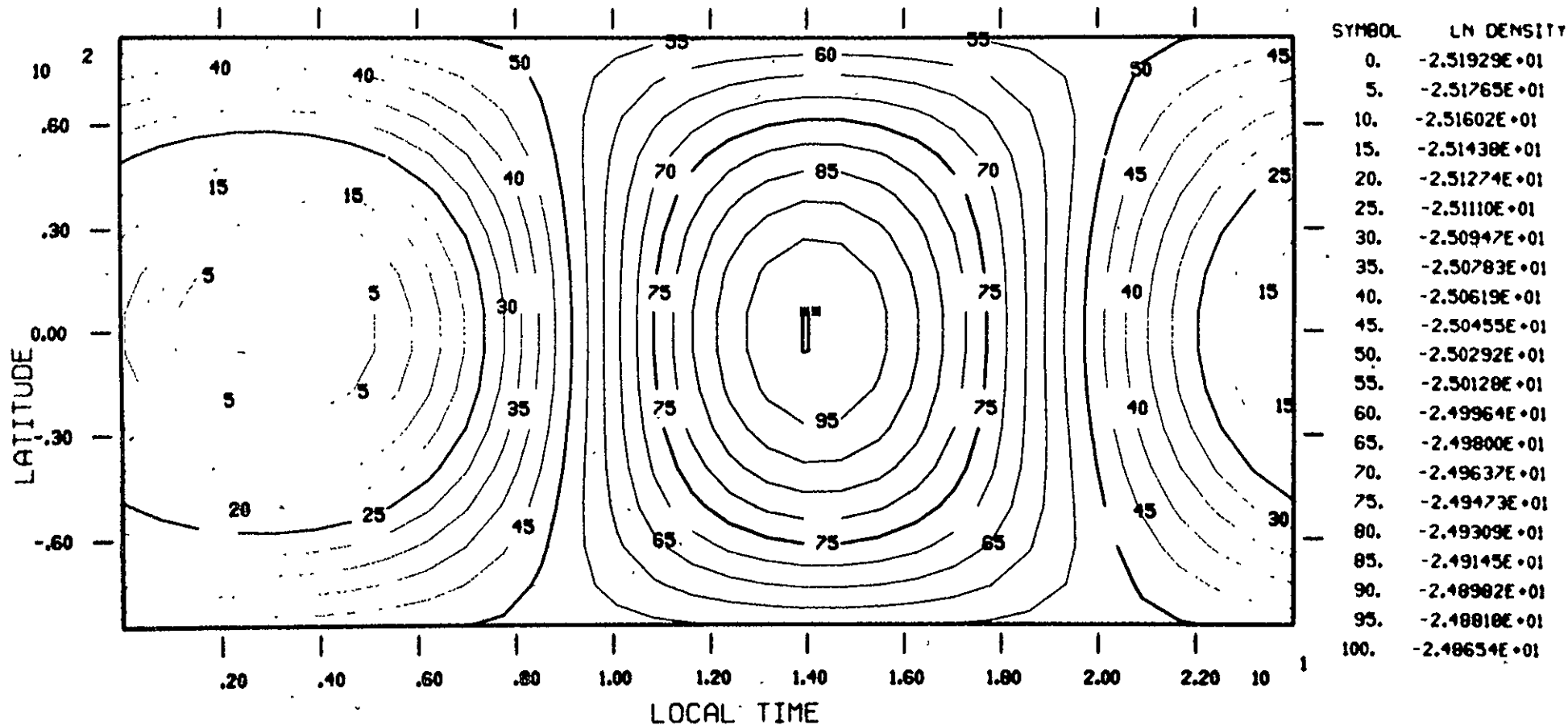


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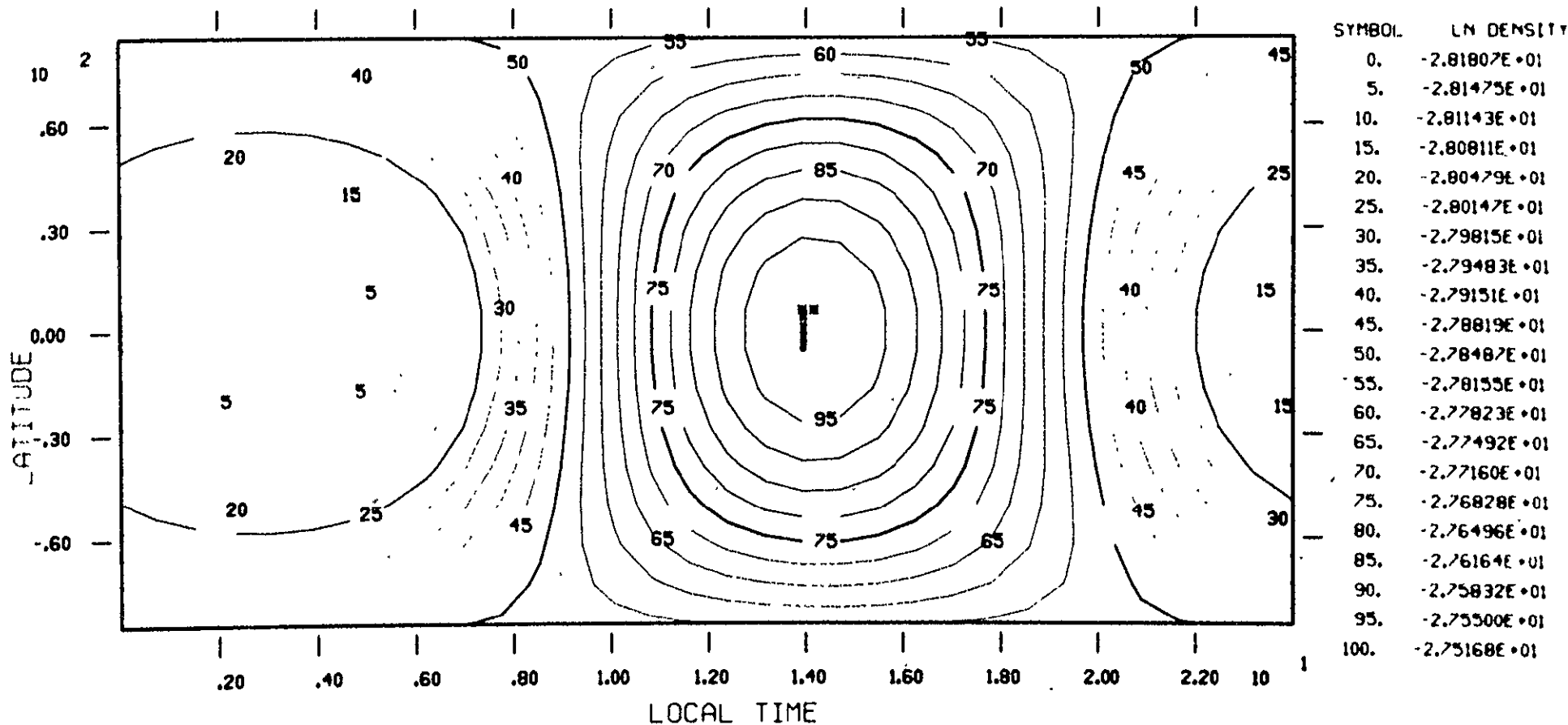


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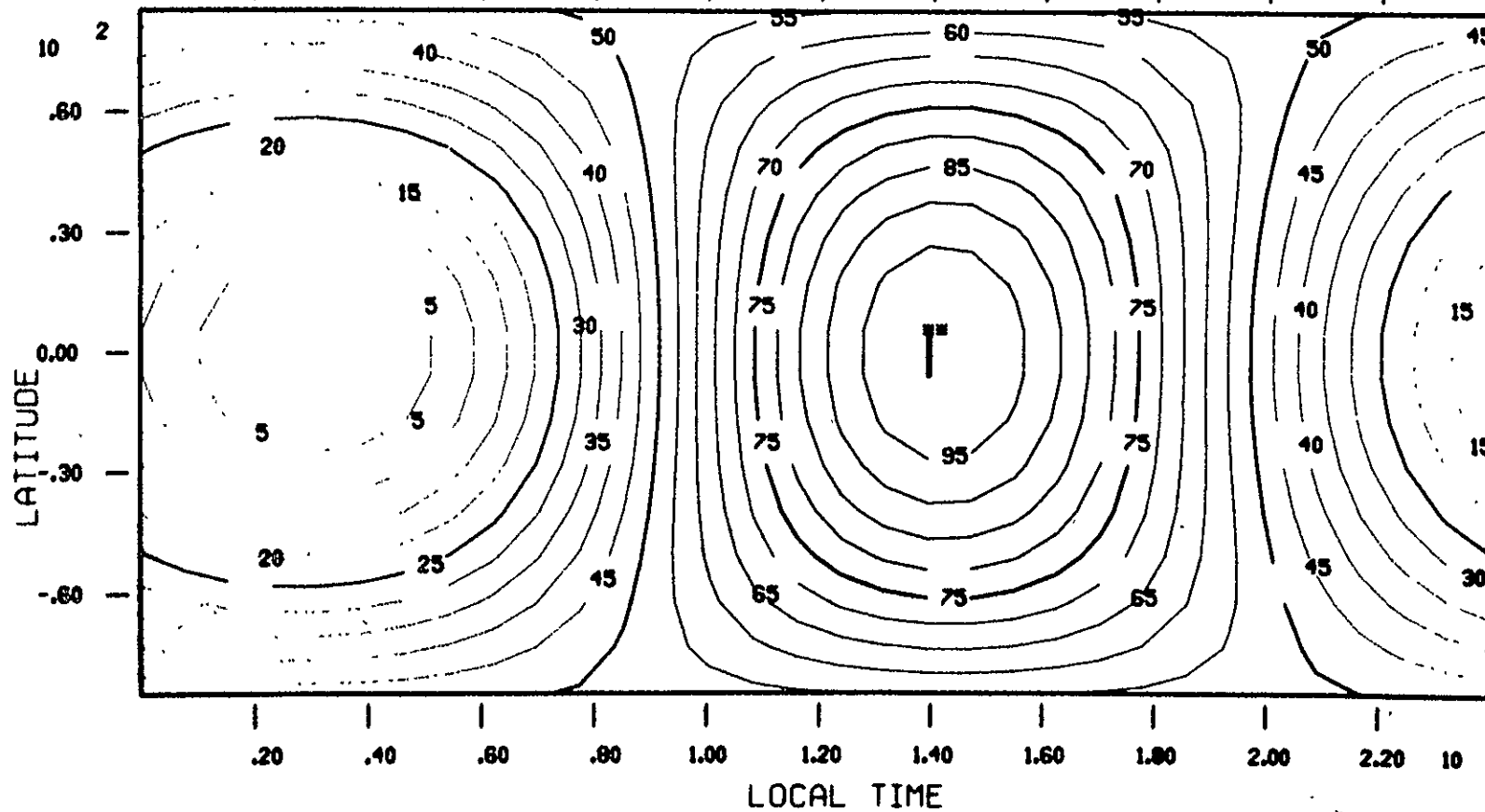
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ATMOSPHERIC DENSITY

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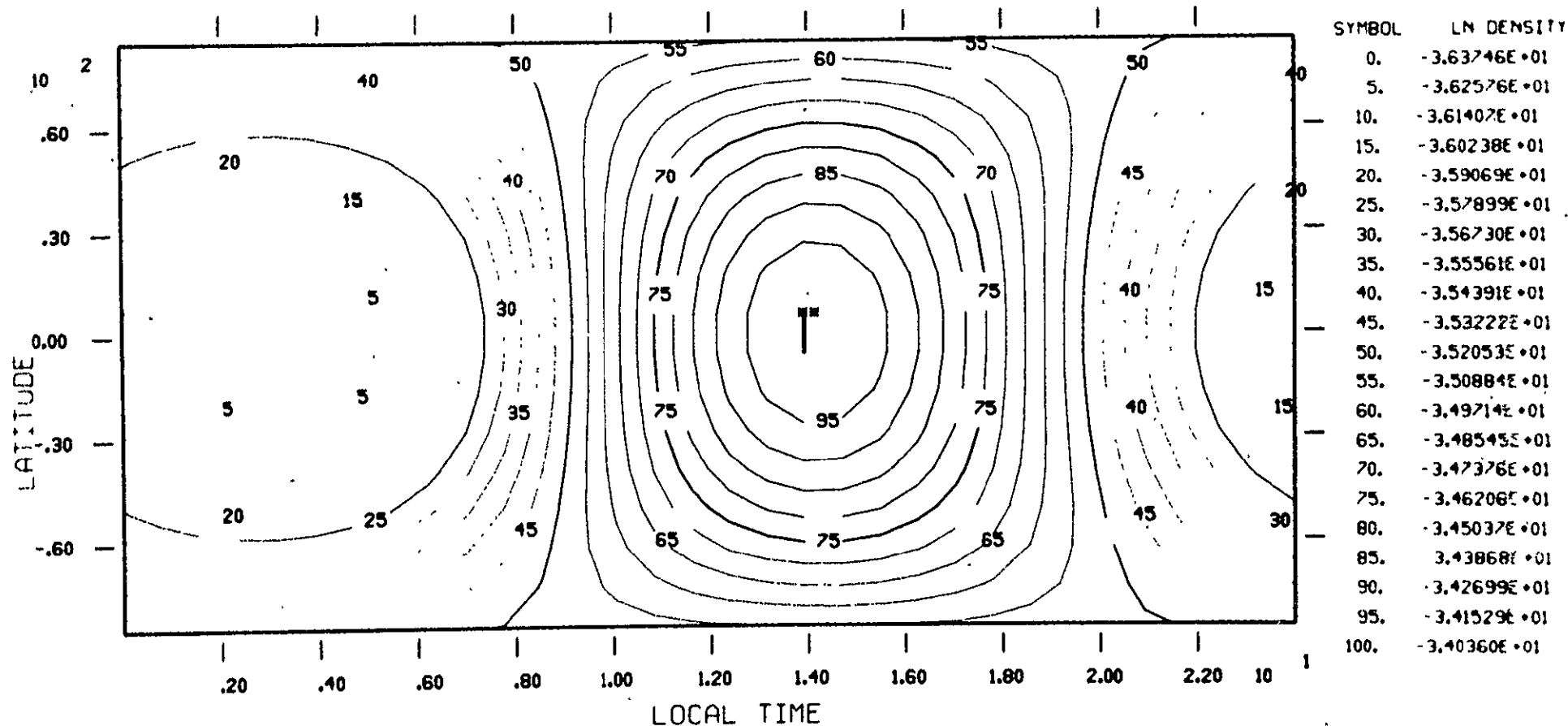


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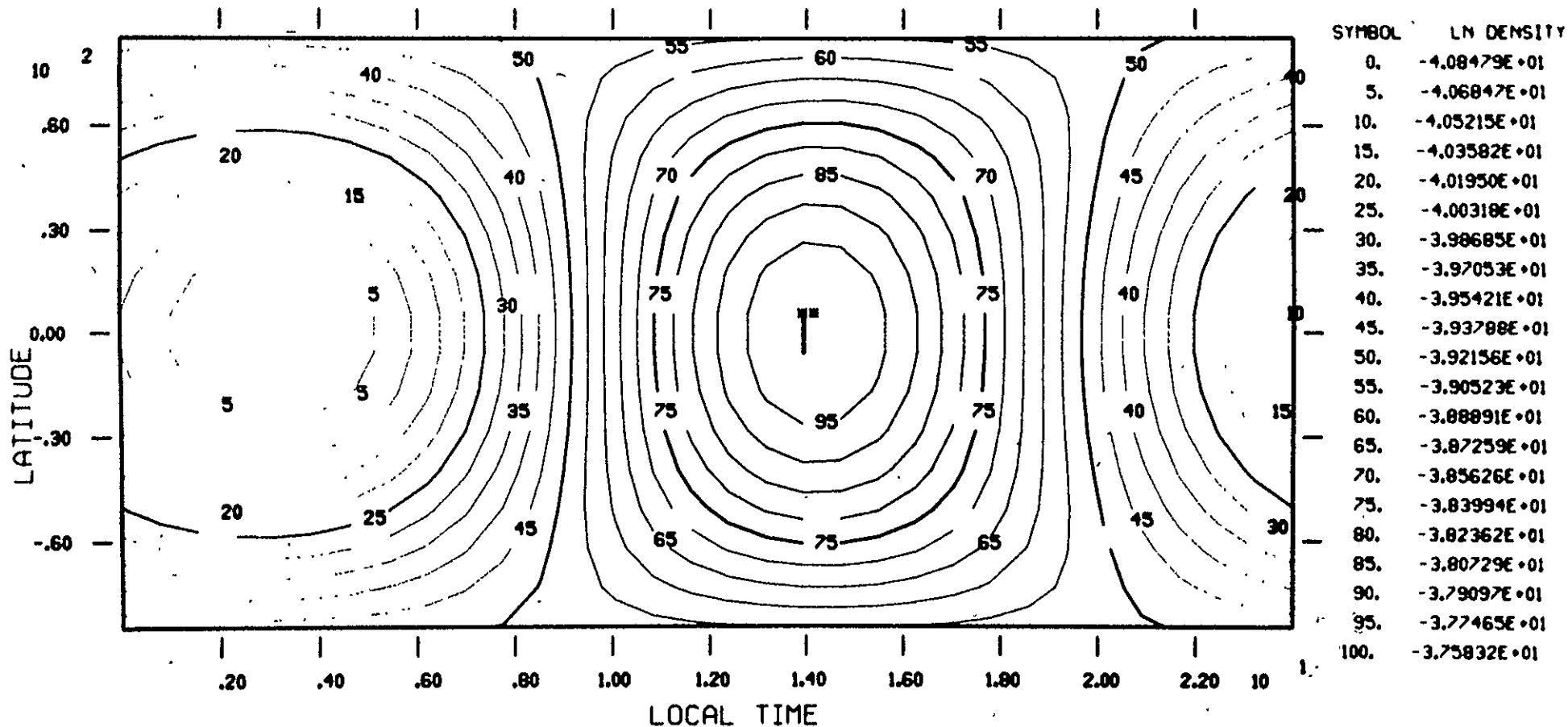
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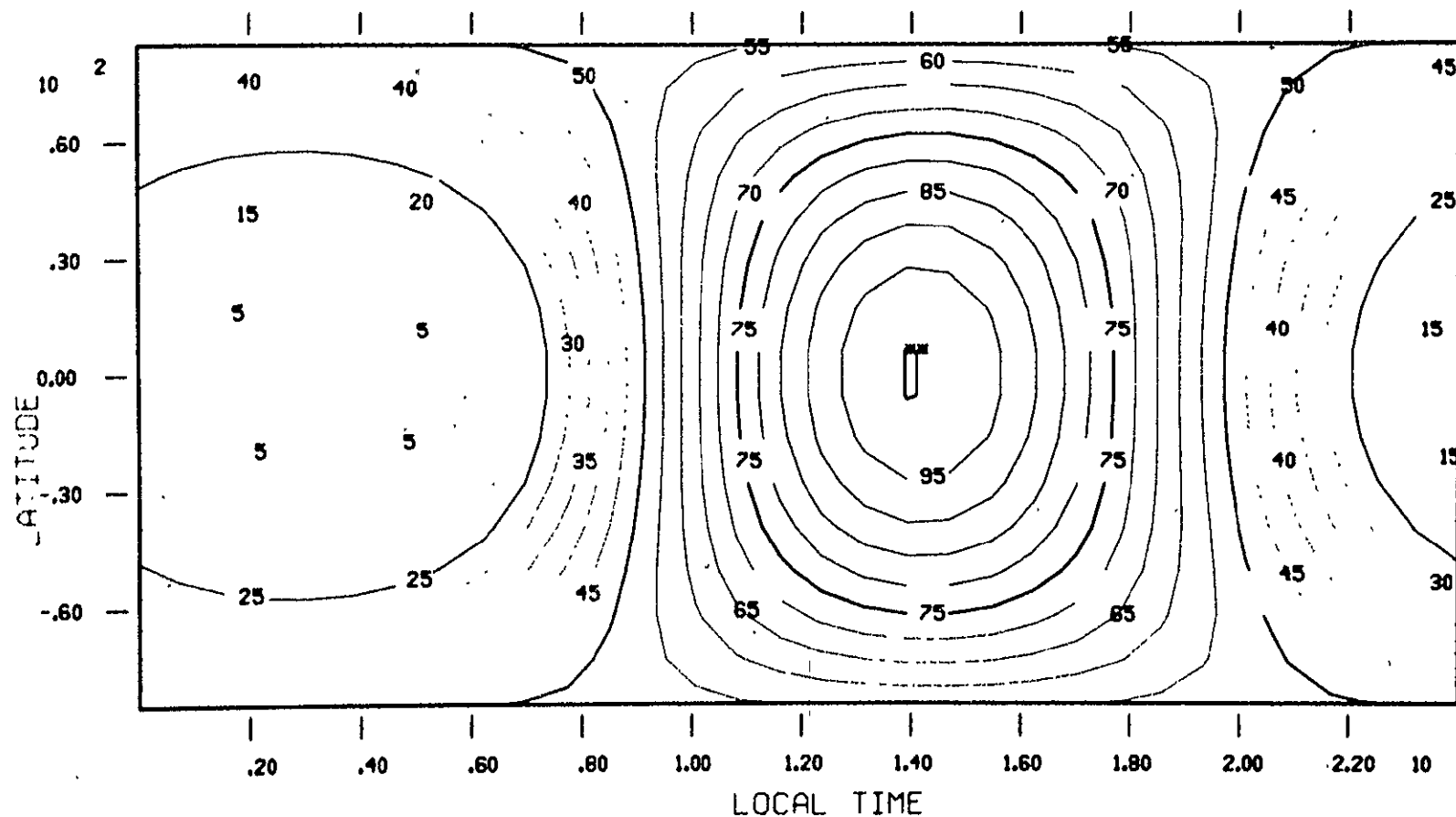
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MOLECULAR OXYGEN 119.0 KM 10.7 CM FLUX= 92.0 DAY 80.



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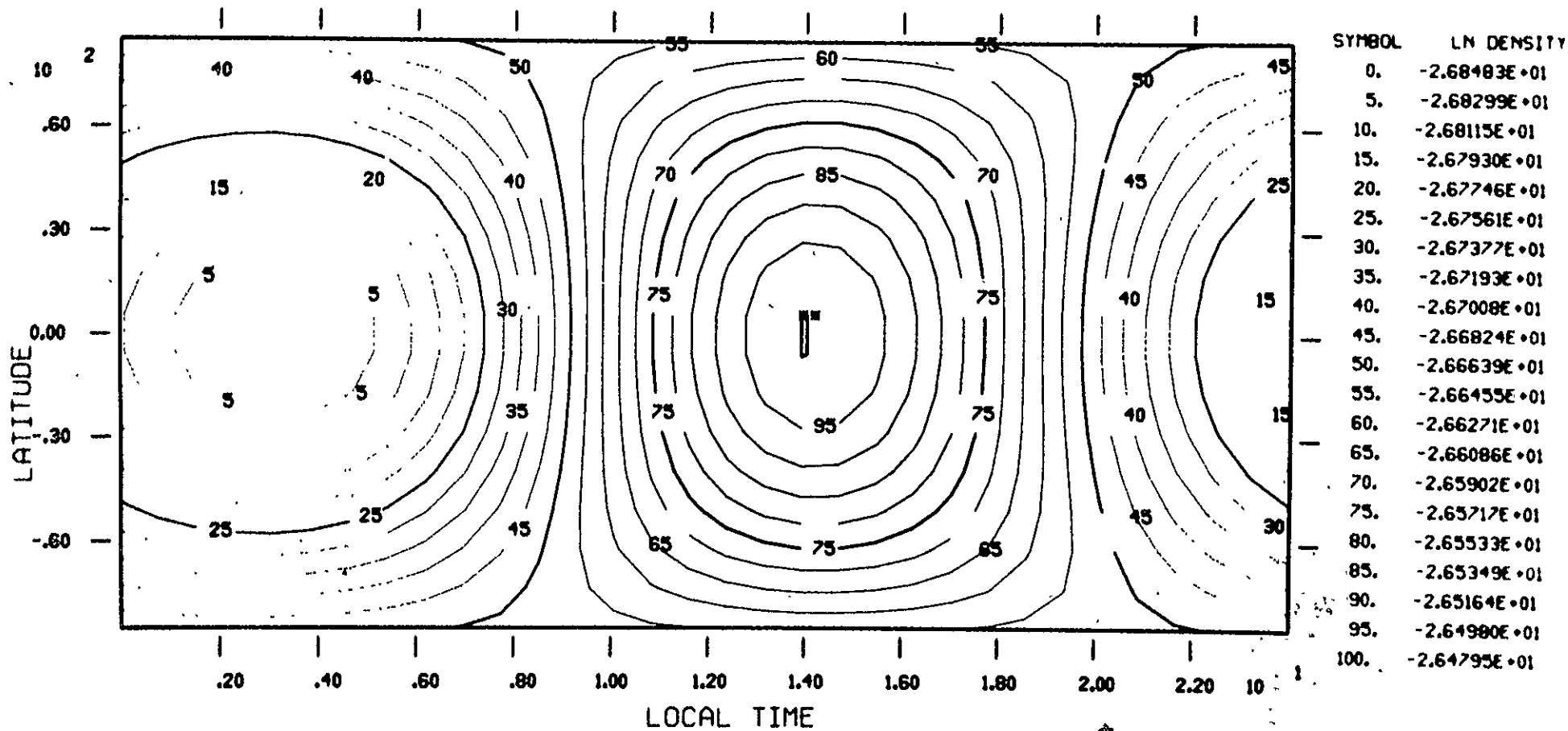
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143.0 KM

10.7 CM FLUX= 92.0

DAY 80.

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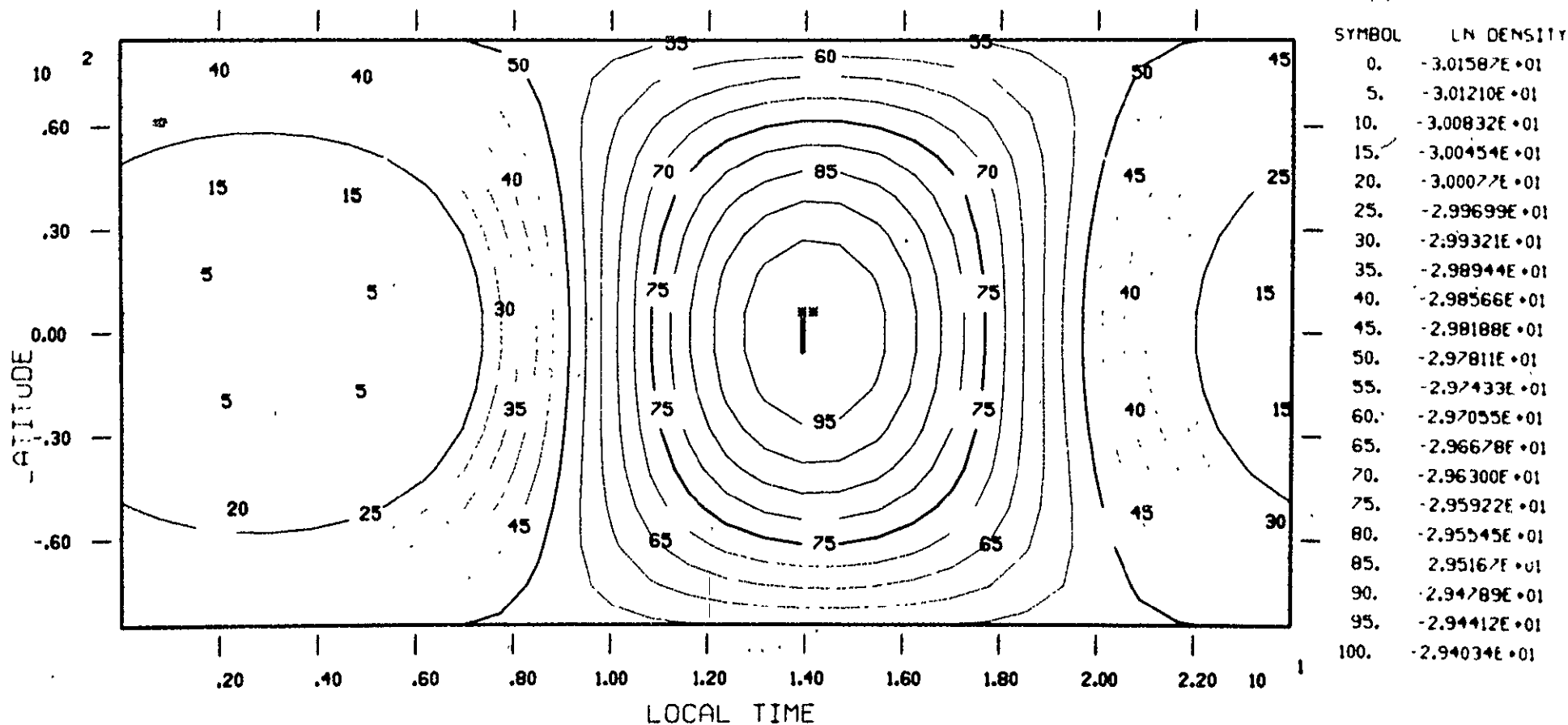


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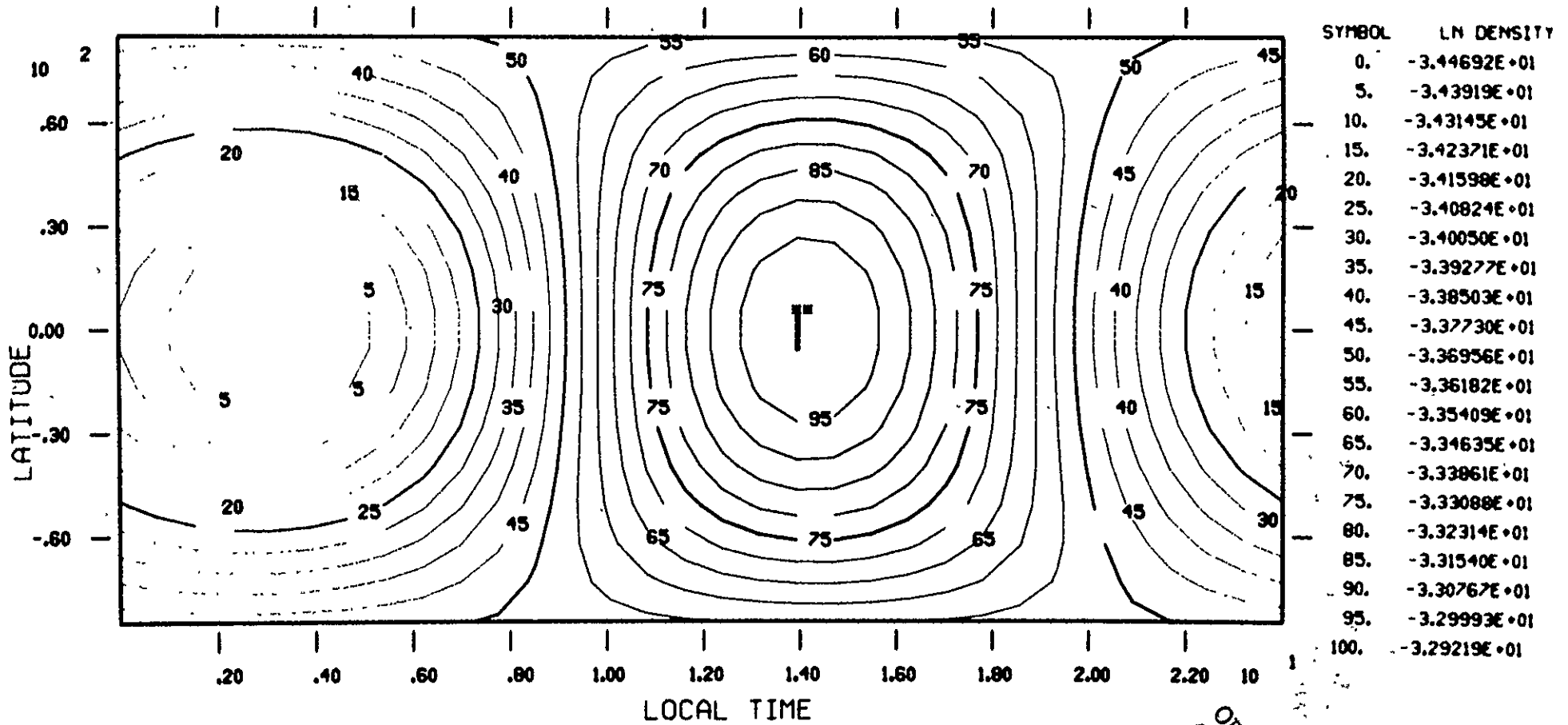
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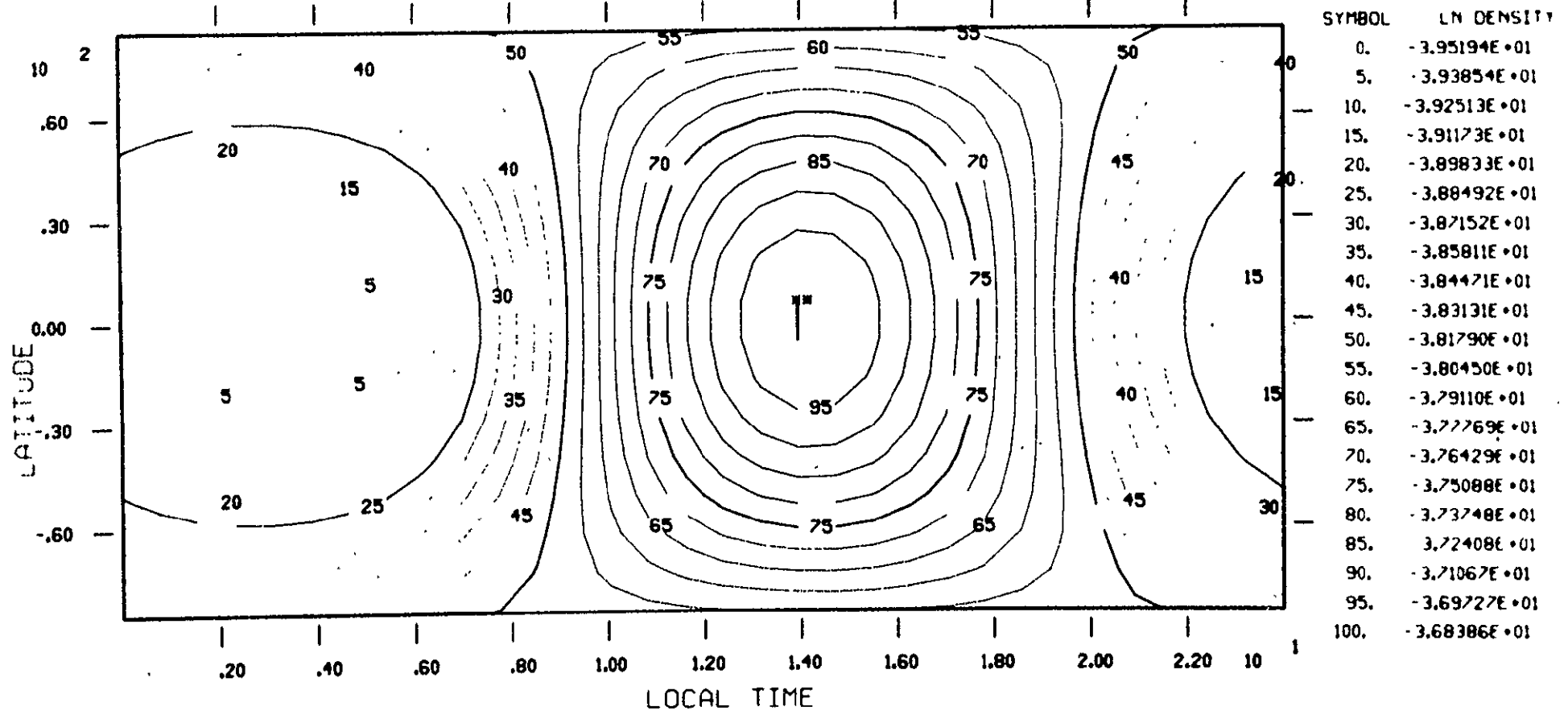
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MOLECULAR OXYGEN

365.0 KM

10.7 CM FLUX= 92.0

DAY 80.



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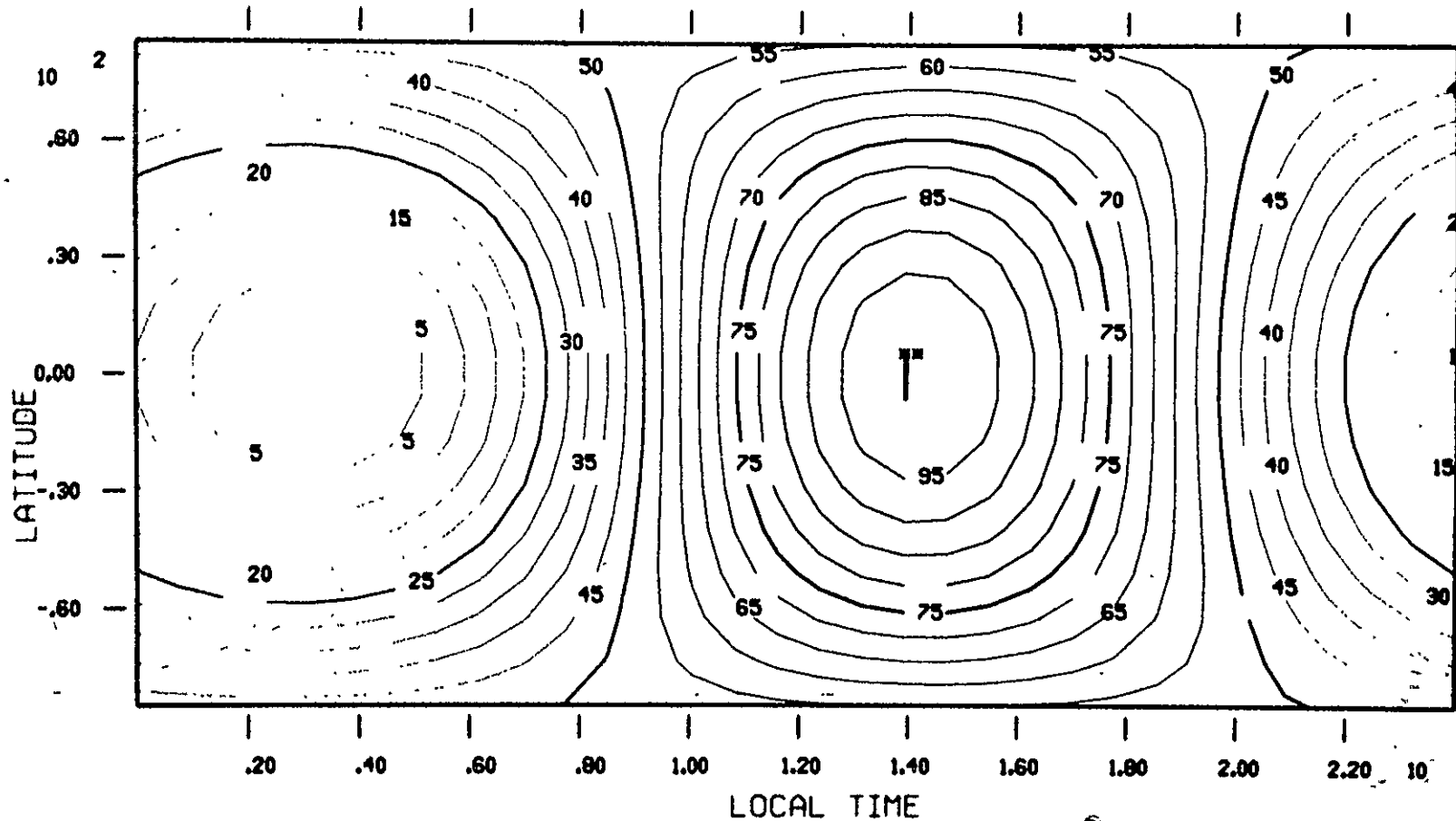
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DAY 80.

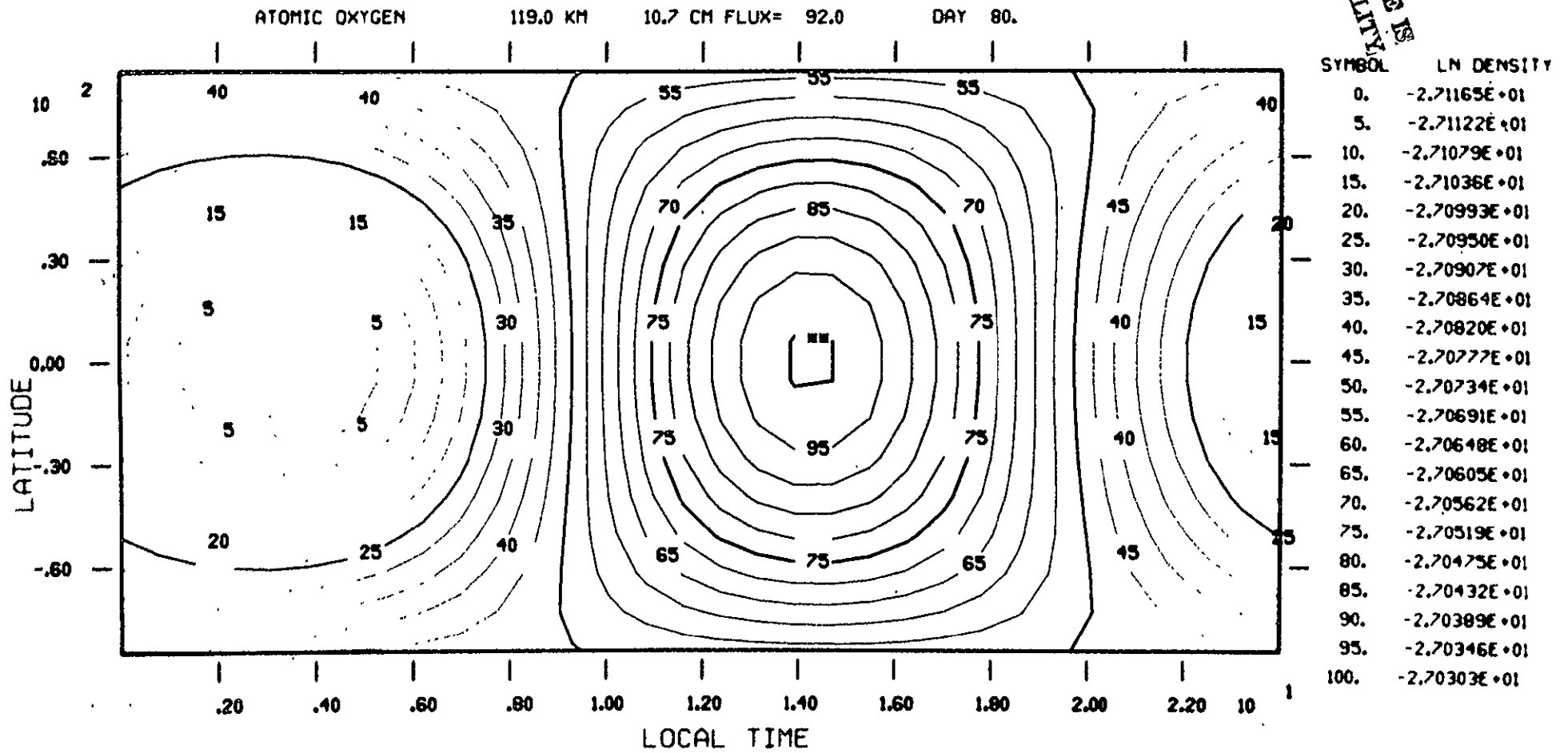
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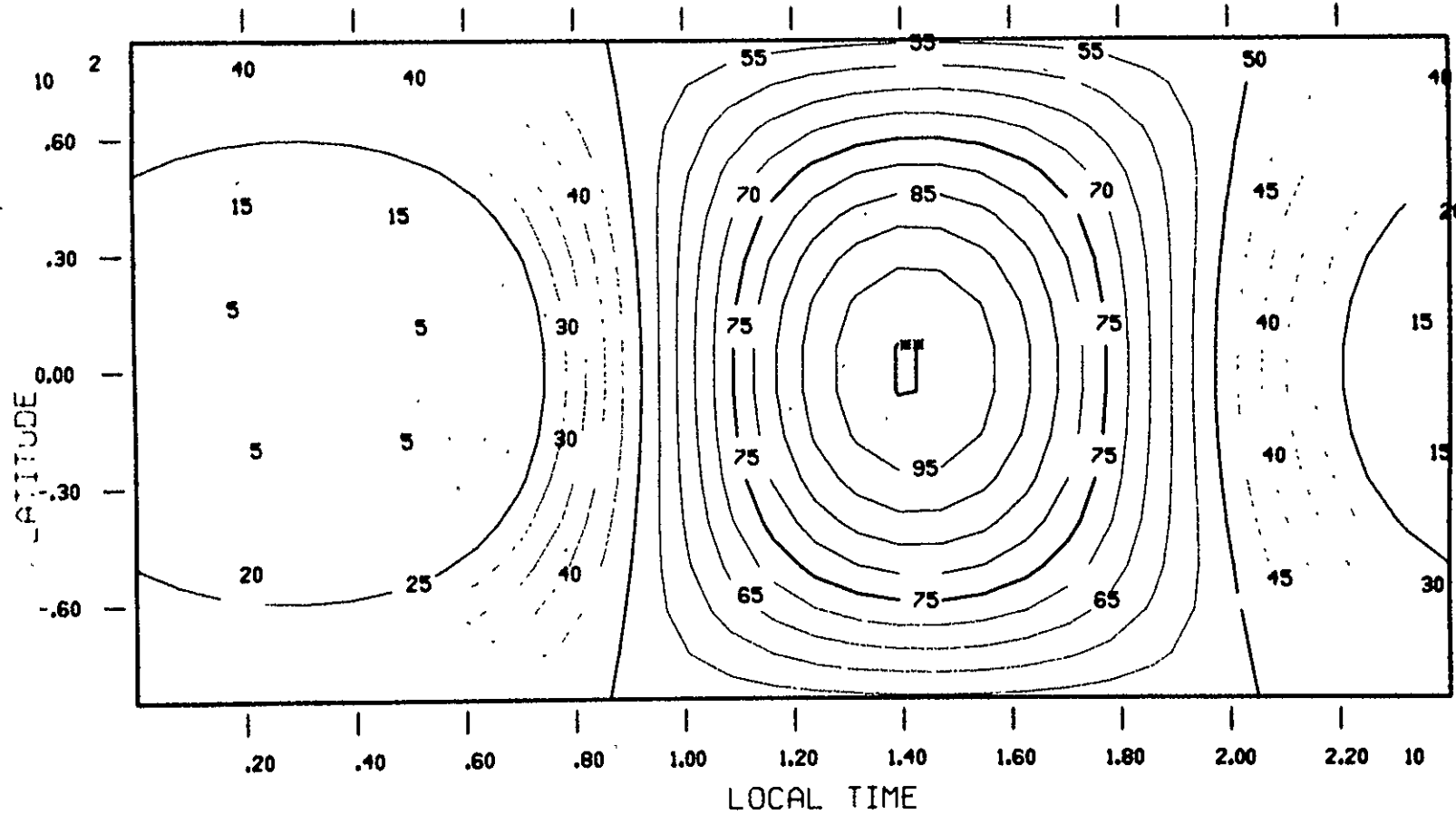
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10.7 CM FLUX= 92.0

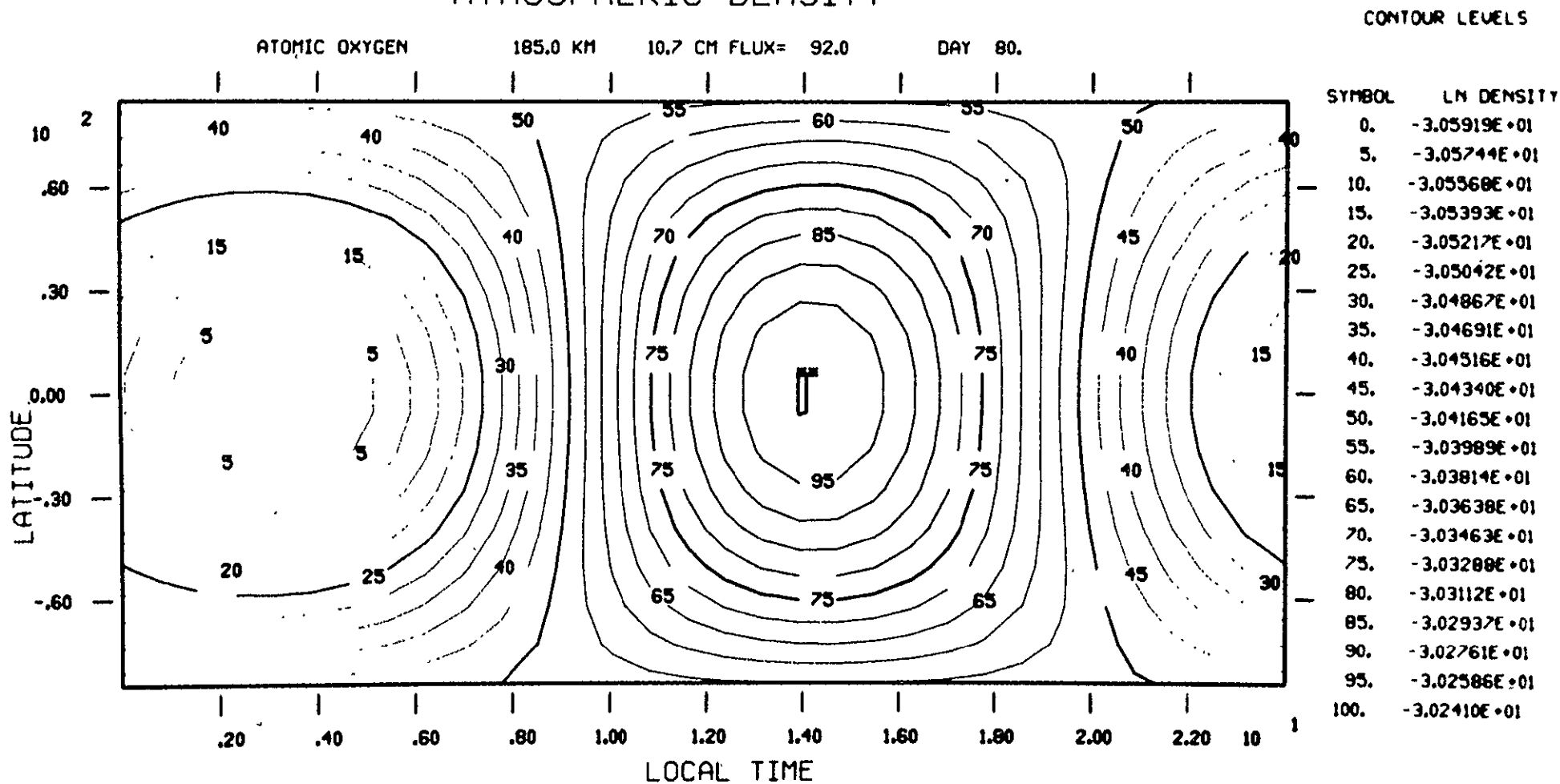
DAY 80.



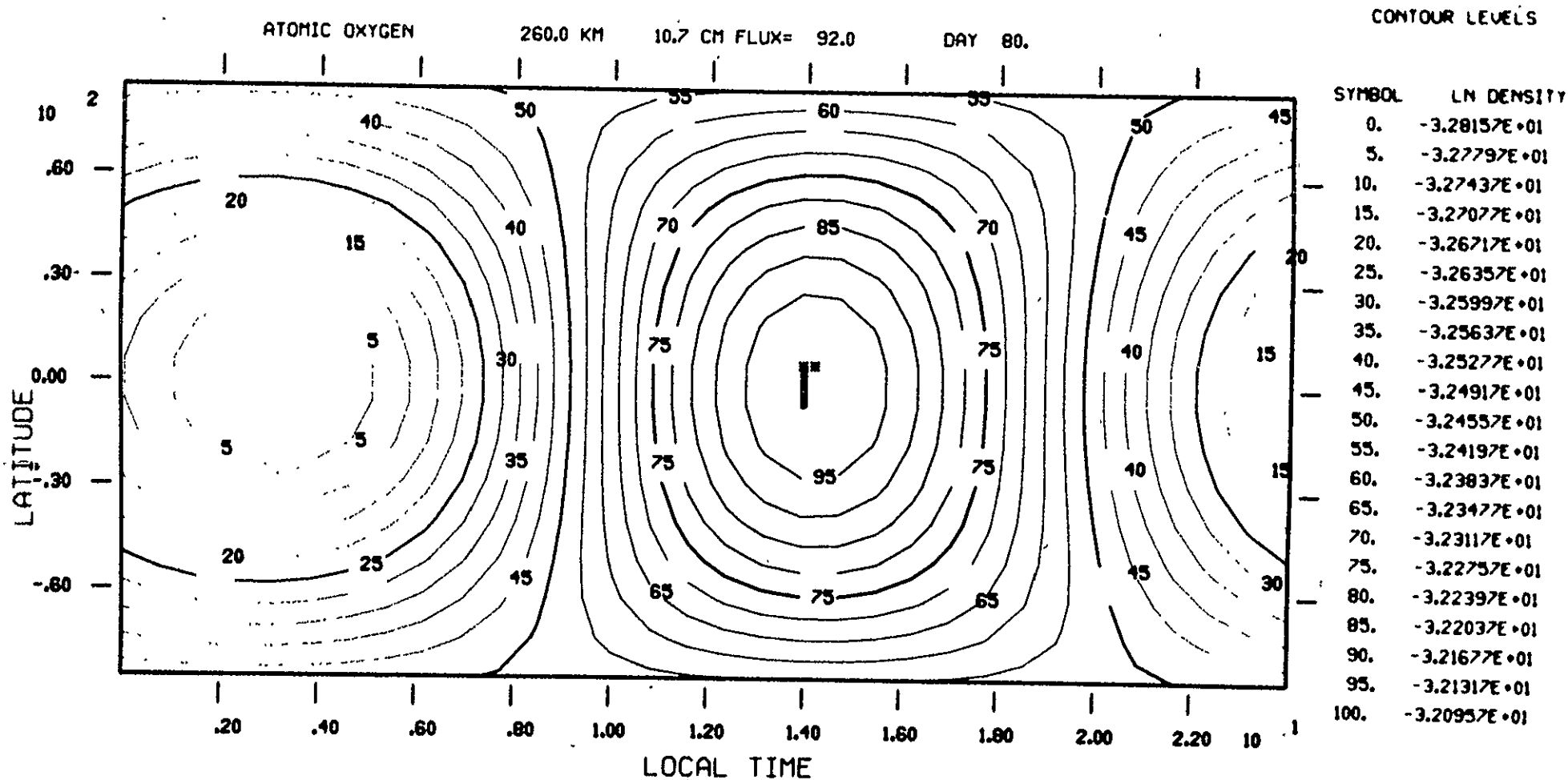
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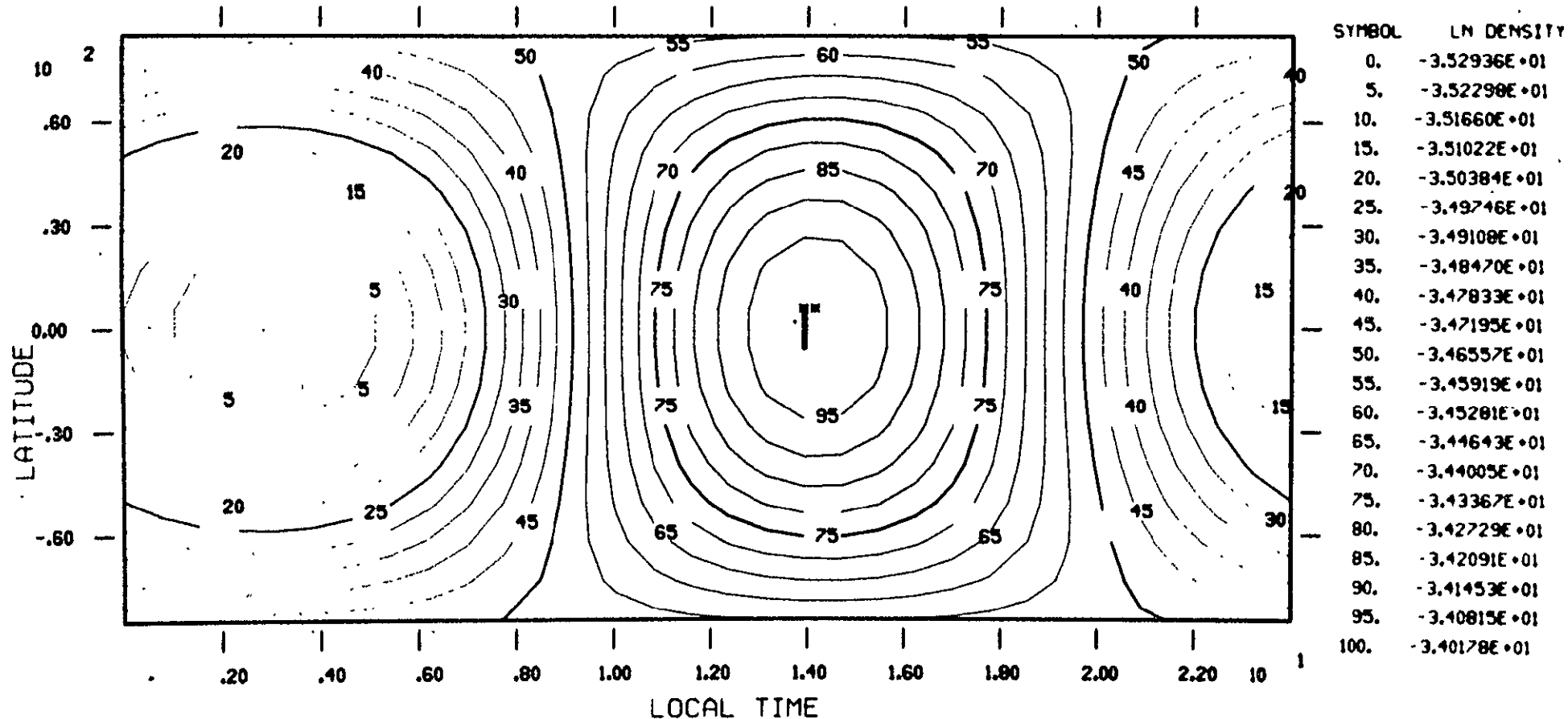
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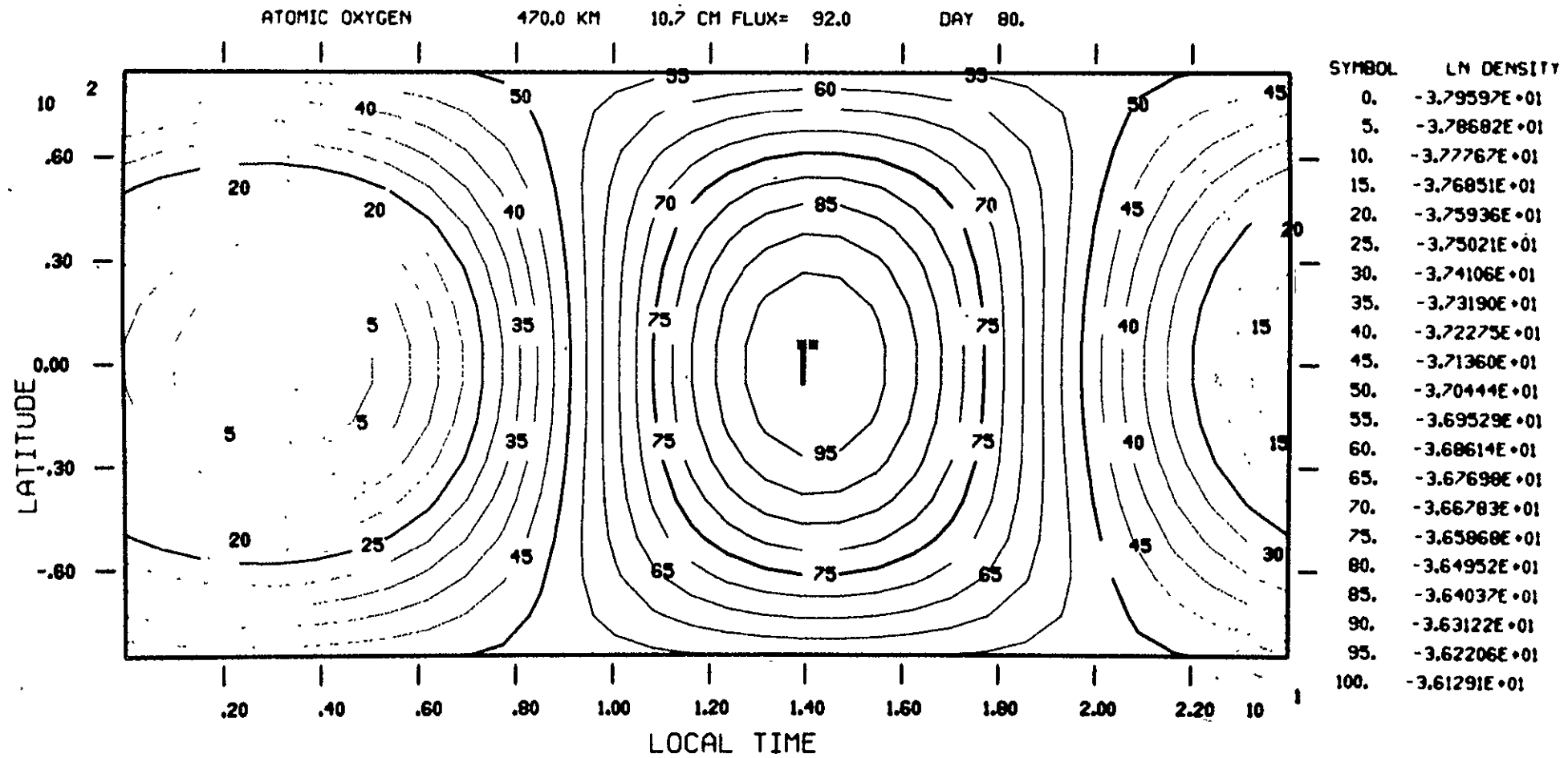
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10.7 CM FLUX= 92.0

DAY 80.



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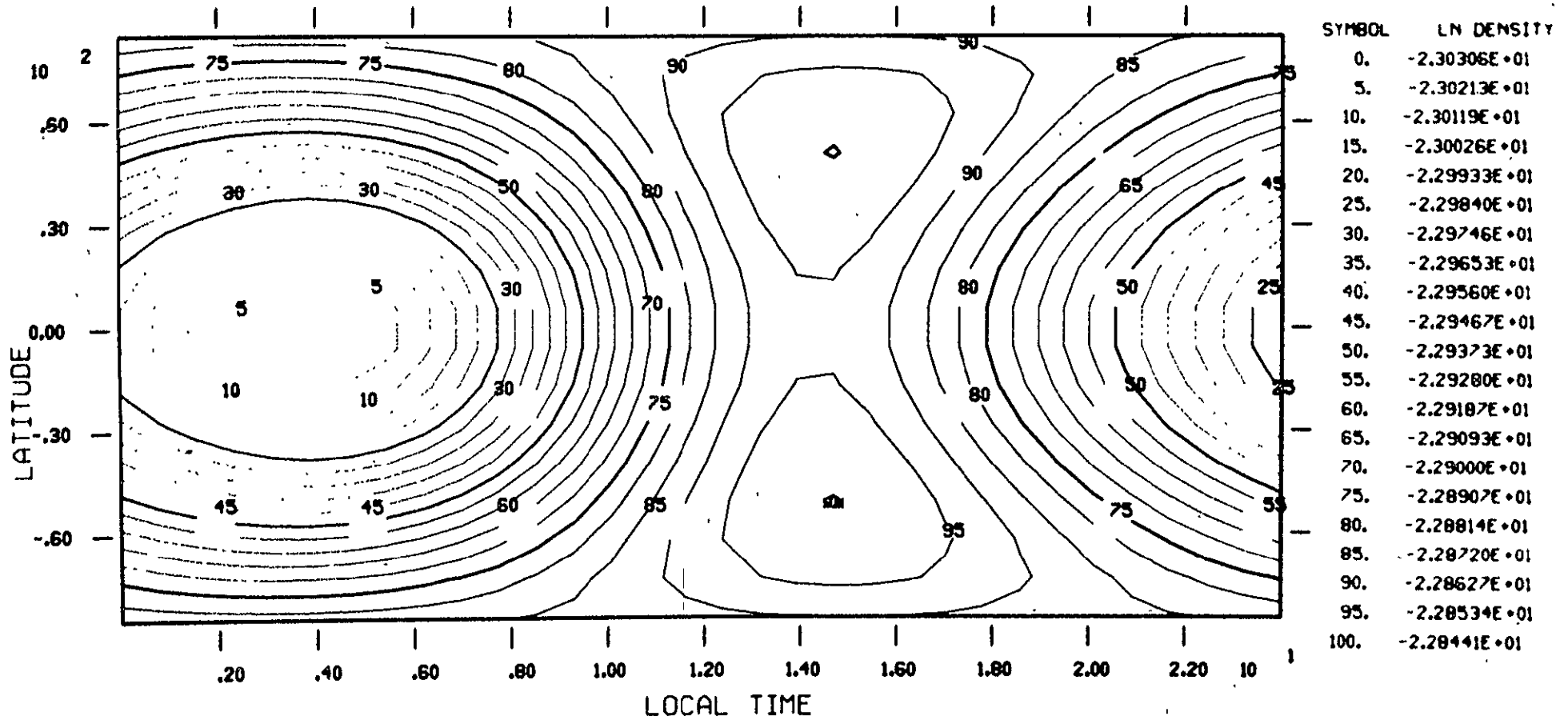


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MOLECULAR NITROGEN 119.0 KM 10.7 CM FLUX= 92.0 DAY 80.



ATMOSPHERIC DENSITY

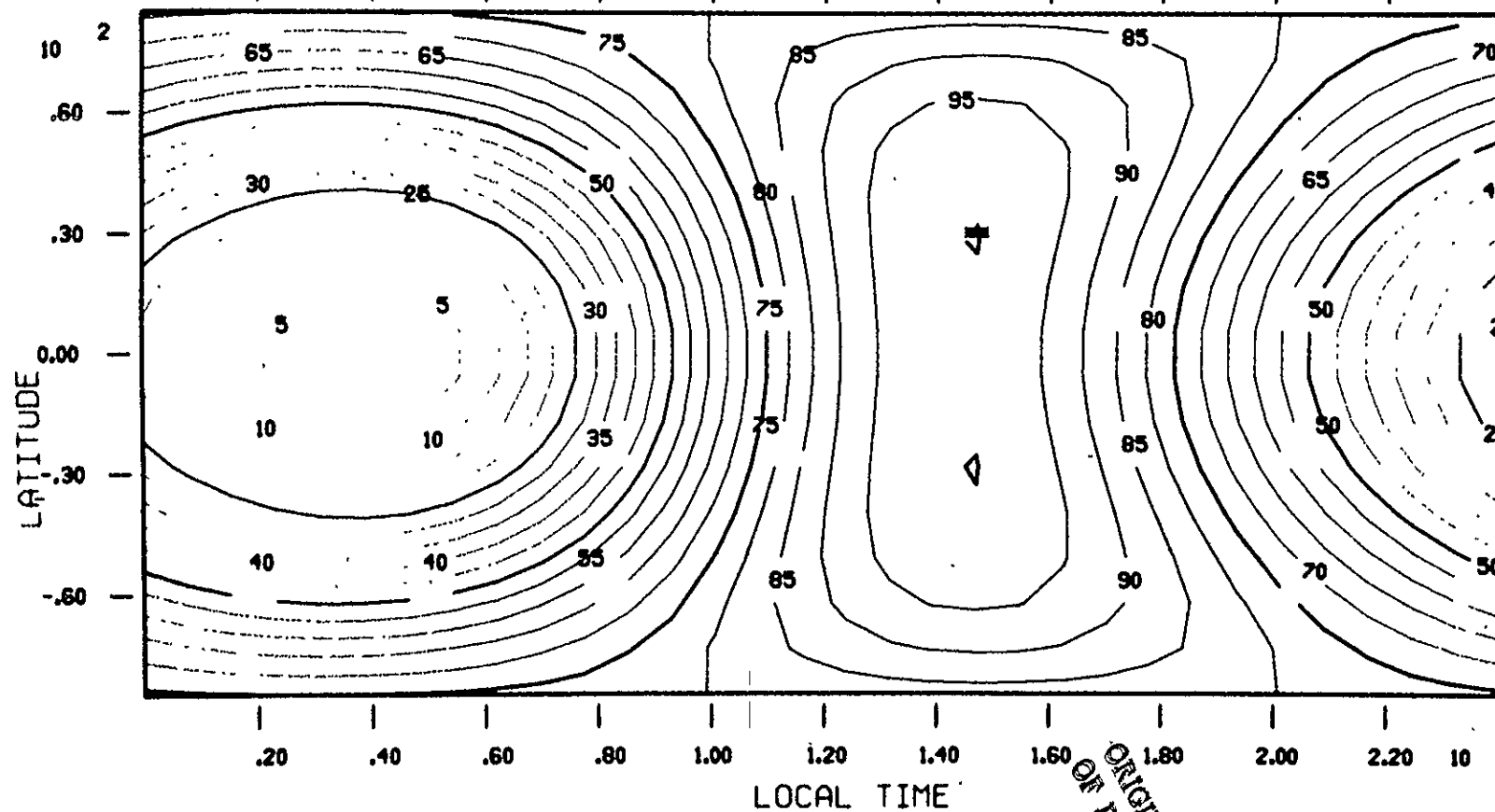
MOLECULAR NITROGEN

143.0 KM

10.7 CM FLUX= 92.0

DAY 80.

CONTOUR LEVELS



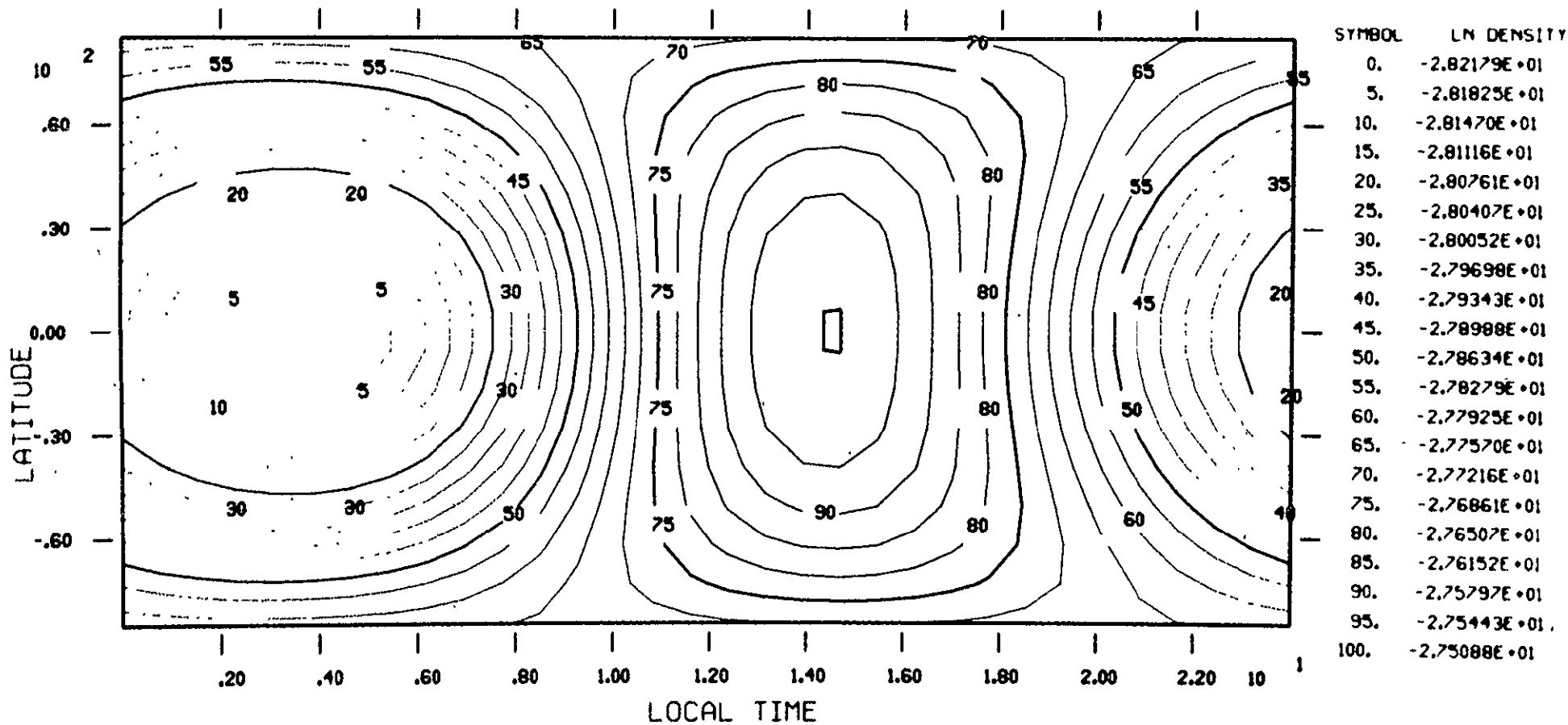
SYMBOL	LN DENSITY
0.	-2.52221E+01
5.	-2.52044E+01
10.	-2.51867E+01
15.	-2.51690E+01
20.	-2.51514E+01
25.	-2.51337E+01
30.	-2.51160E+01
35.	-2.50983E+01
40.	-2.50806E+01
45.	-2.50629E+01
50.	-2.50452E+01
55.	-2.50275E+01
60.	-2.50098E+01
65.	-2.49921E+01
70.	-2.49744E+01
75.	-2.49567E+01
80.	-2.49390E+01
85.	-2.49214E+01
90.	-2.49037E+01
95.	-2.48860E+01
100.	-2.48683E+01

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CONTAINS LEVELS

ATMOSPHERIC DENSITY

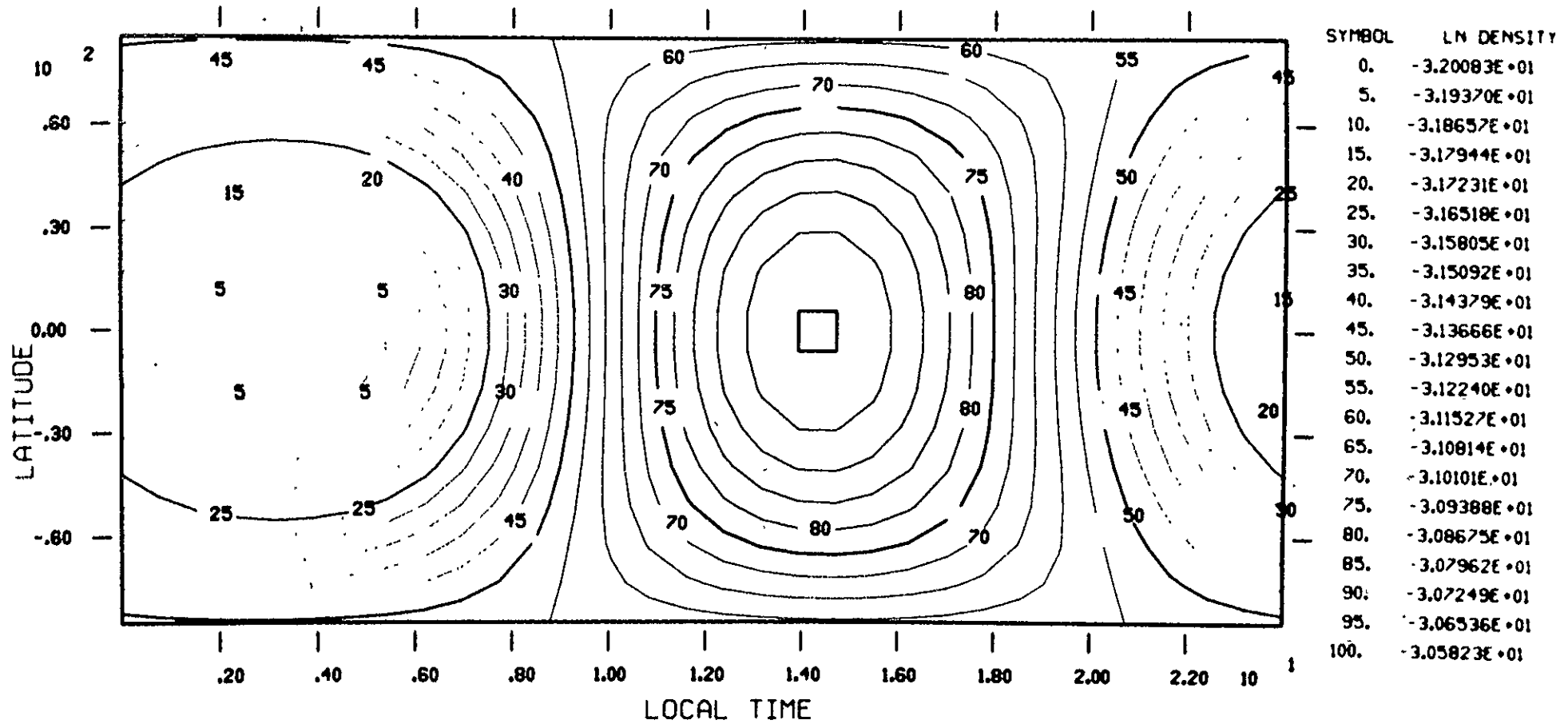
MOLECULAR NITROGEN 185.0 KM 10.7 CM FLUX= 92.0 DAY 80.



ATMOSPHERIC DENSITY

MOLECULAR NITROGEN 260.0 KM 10.7 CM FLUX= 92.0 DAY 80.

CONTOUR LEVELS

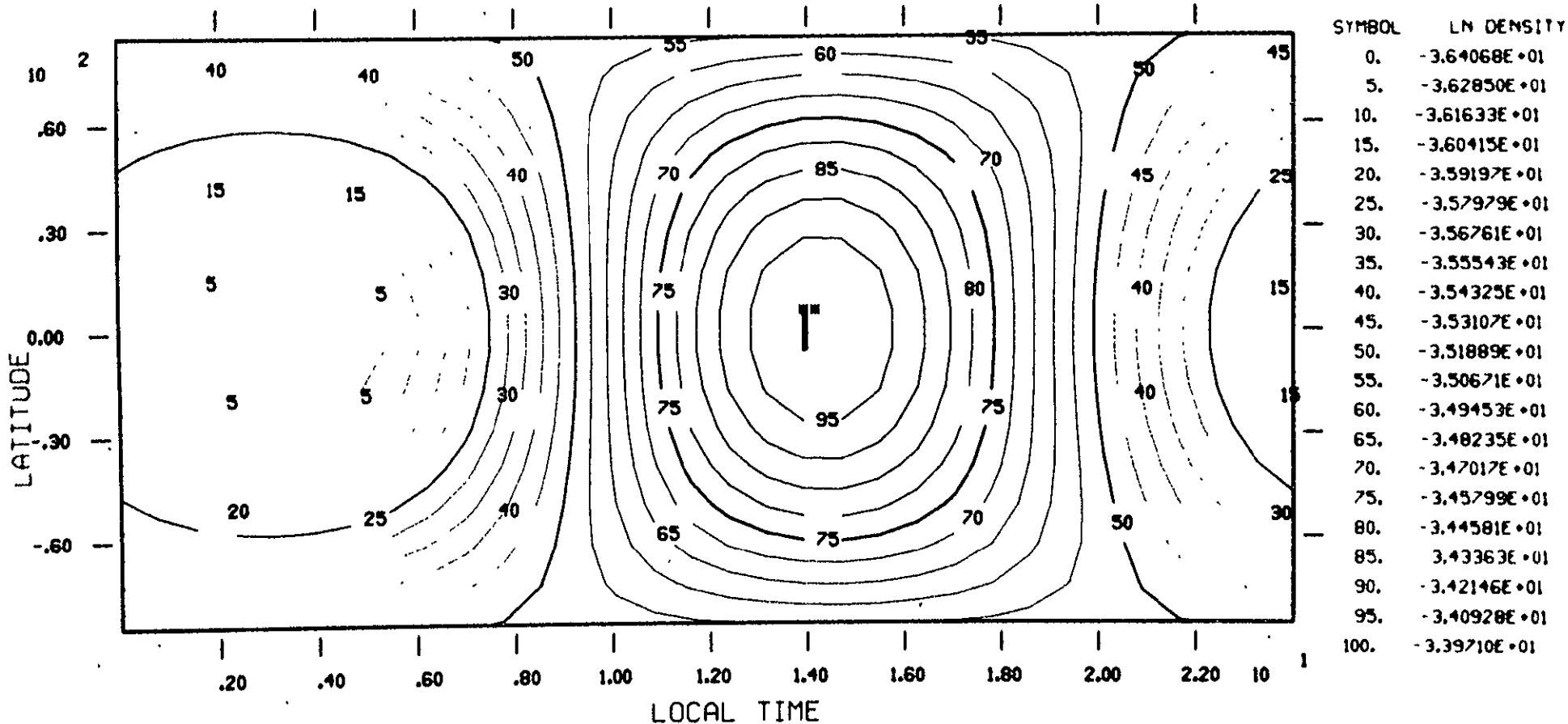


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ATMOSPHERIC DENSITY

CONTOUR LEVELS

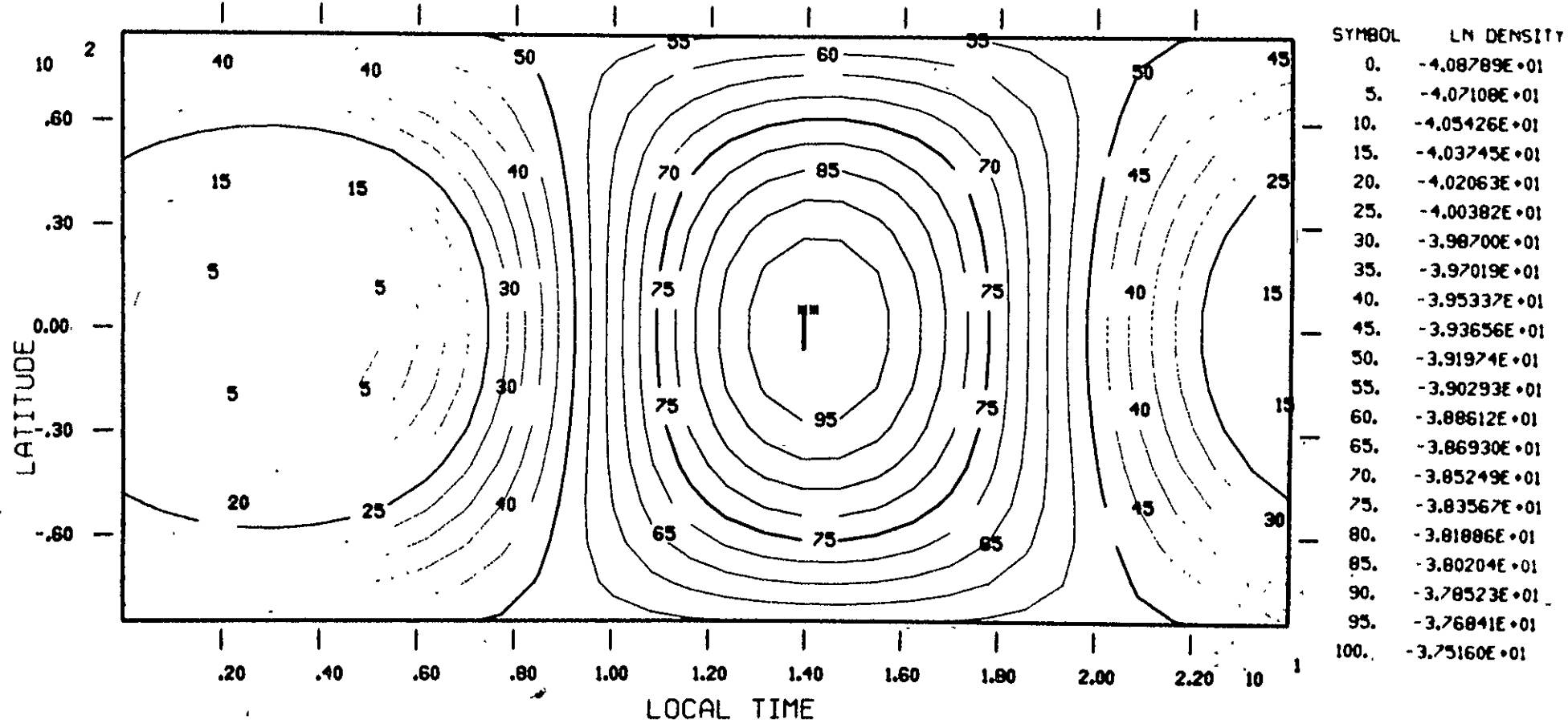
MOLECULAR NITROGEN 365.0 KM 10.7 CM FLUX= 92.0 DAY 80.



ATMOSPHERIC DENSITY

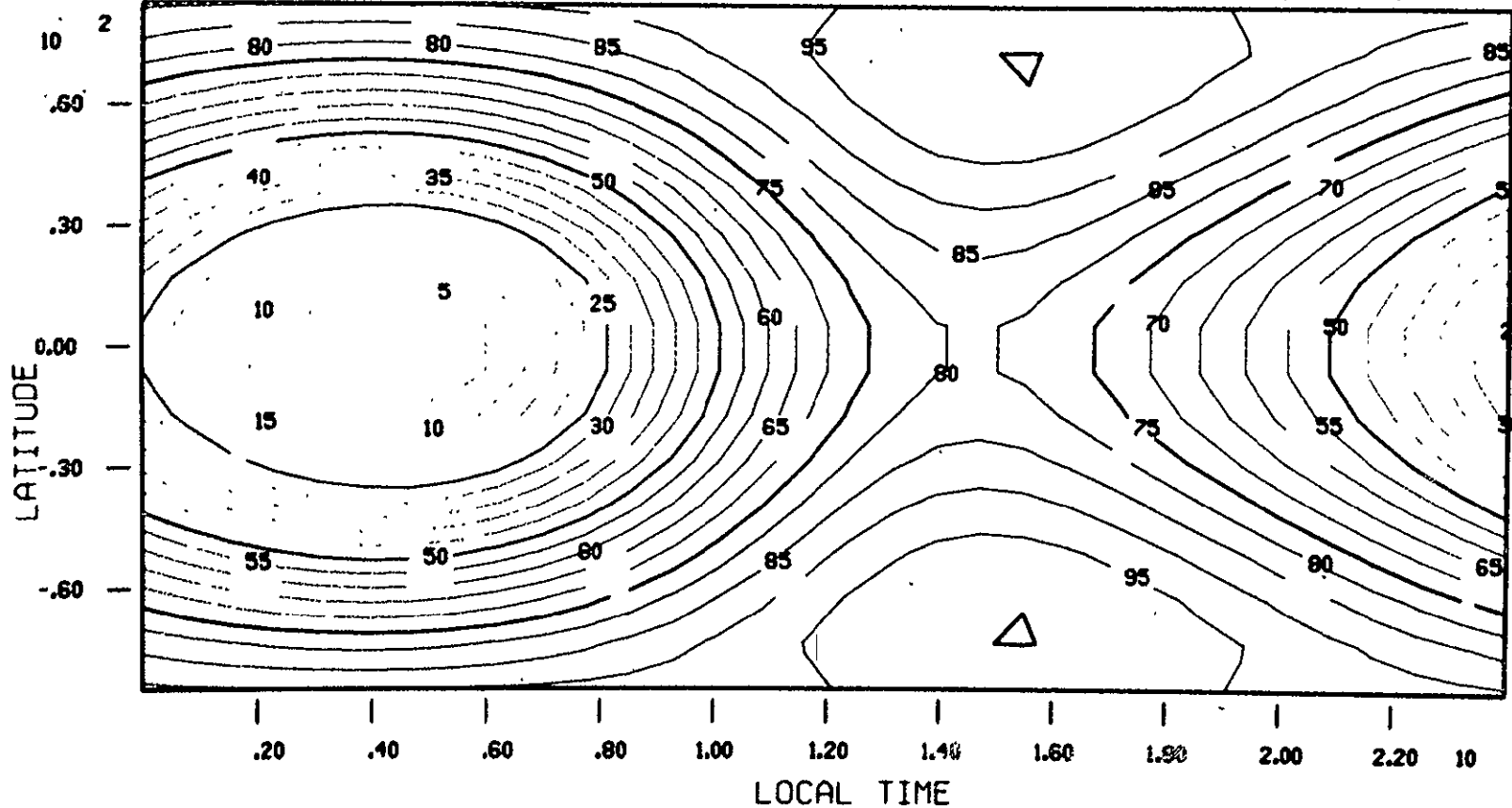
MOLECULAR NITROGEN 470.0 KM 10.7 CM FLUX= 92.0 DAY 80.

CONTOUR LEVELS



ATMOSPHERIC DENSITY

MOLECULAR OXYGEN 119.0 KM 10.7 CM FLUX= 92.0 DAY 80.



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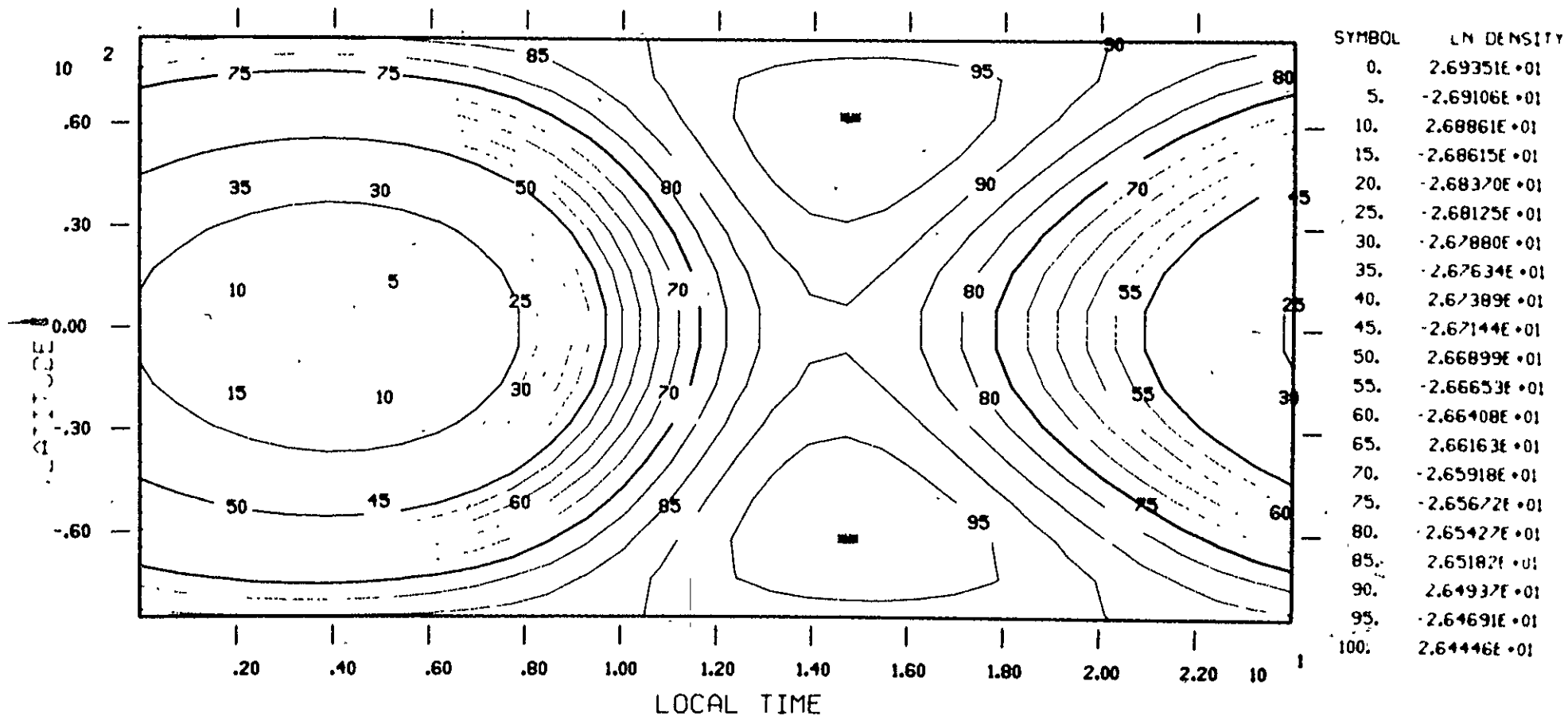
CONTOUR LEVELS

SYMBOL	LN DENSITY
0.	-2.45261E+01
5.	-2.45122E+01
10.	-2.44983E+01
15.	-2.44844E+01
20.	-2.44706E+01
25.	-2.44567E+01
30.	-2.44428E+01
35.	-2.44289E+01
40.	-2.44150E+01
45.	-2.44011E+01
50.	-2.43872E+01
55.	-2.43733E+01
60.	-2.43594E+01
65.	-2.43455E+01
70.	-2.43316E+01
75.	-2.43177E+01
80.	-2.43038E+01
85.	-2.42899E+01
90.	-2.42760E+01
95.	-2.42621E+01
100.	-2.42482E+01

ATMOSPHERIC DENSITY

MOLECULAR OXYGEN 143.0 KM 10.7 CM FLUX= 92.0 DAY 80.

CONTOUR LEVELS



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ATMOSPHERIC DENSITY

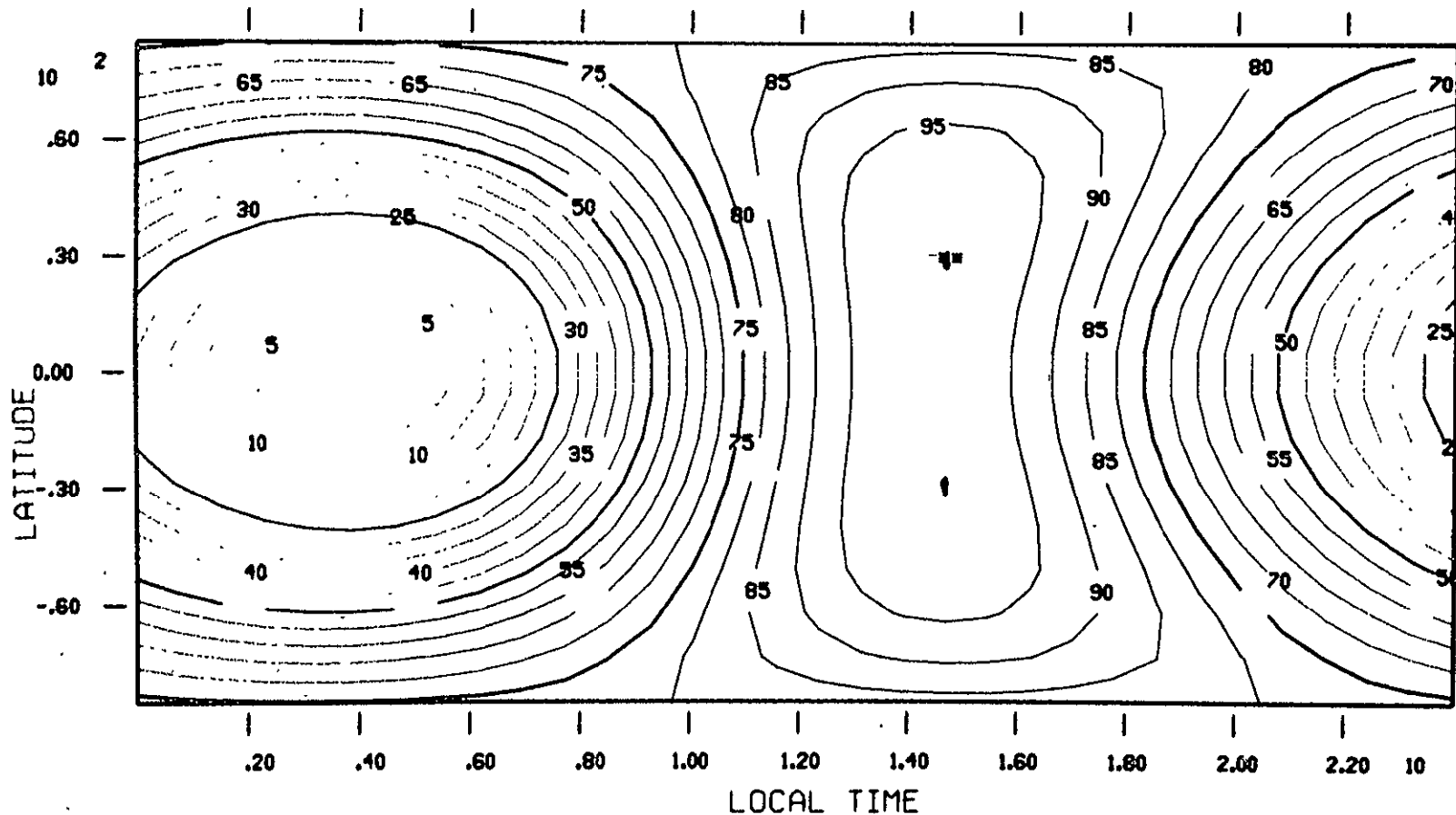
MOLECULAR OXYGEN

185.0 KM

10.7 CM FLUX= 92.0

DAY 80.

CONTOUR LEVELS



SYMBOL	LN DENSITY
0.	-3.02748E+01
5.	-3.02309E+01
10.	-3.01870E+01
15.	-3.01431E+01
20.	-3.00992E+01
25.	-3.00553E+01
30.	-3.00114E+01
35.	-2.99675E+01
40.	-2.99236E+01
45.	-2.98797E+01
50.	-2.98358E+01
55.	-2.97919E+01
60.	-2.97480E+01
65.	-2.97041E+01
70.	-2.96602E+01
75.	-2.96163E+01
80.	-2.95724E+01
85.	-2.95285E+01
90.	-2.94846E+01
95.	-2.94407E+01
100.	-2.93968E+01

ATMOSPHERIC DENSITY

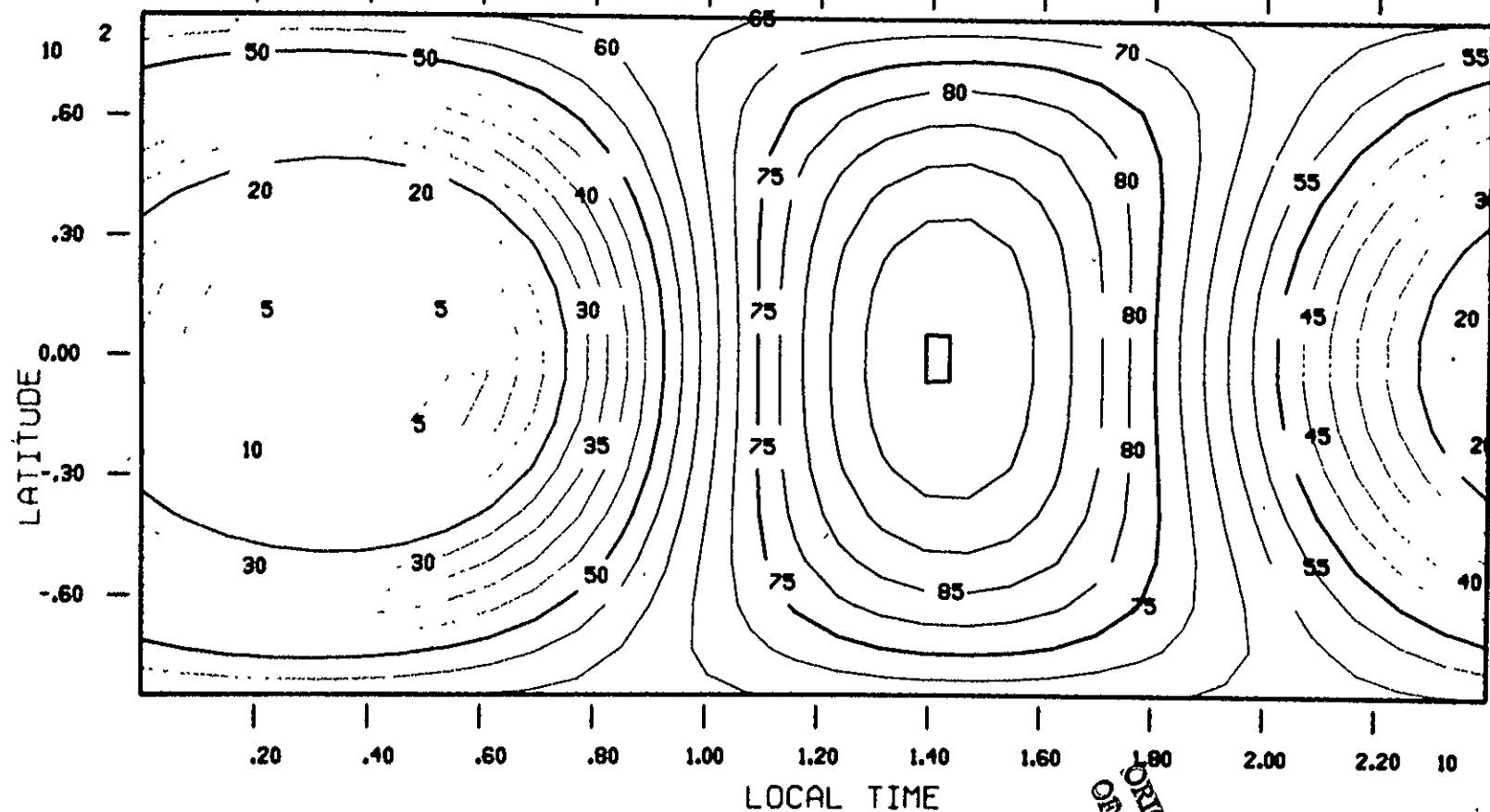
MOLECULAR OXYGEN

260.0 KM

10.7 CM FLUX= 92.0

DAY 80.

CONTOUR LEVELS

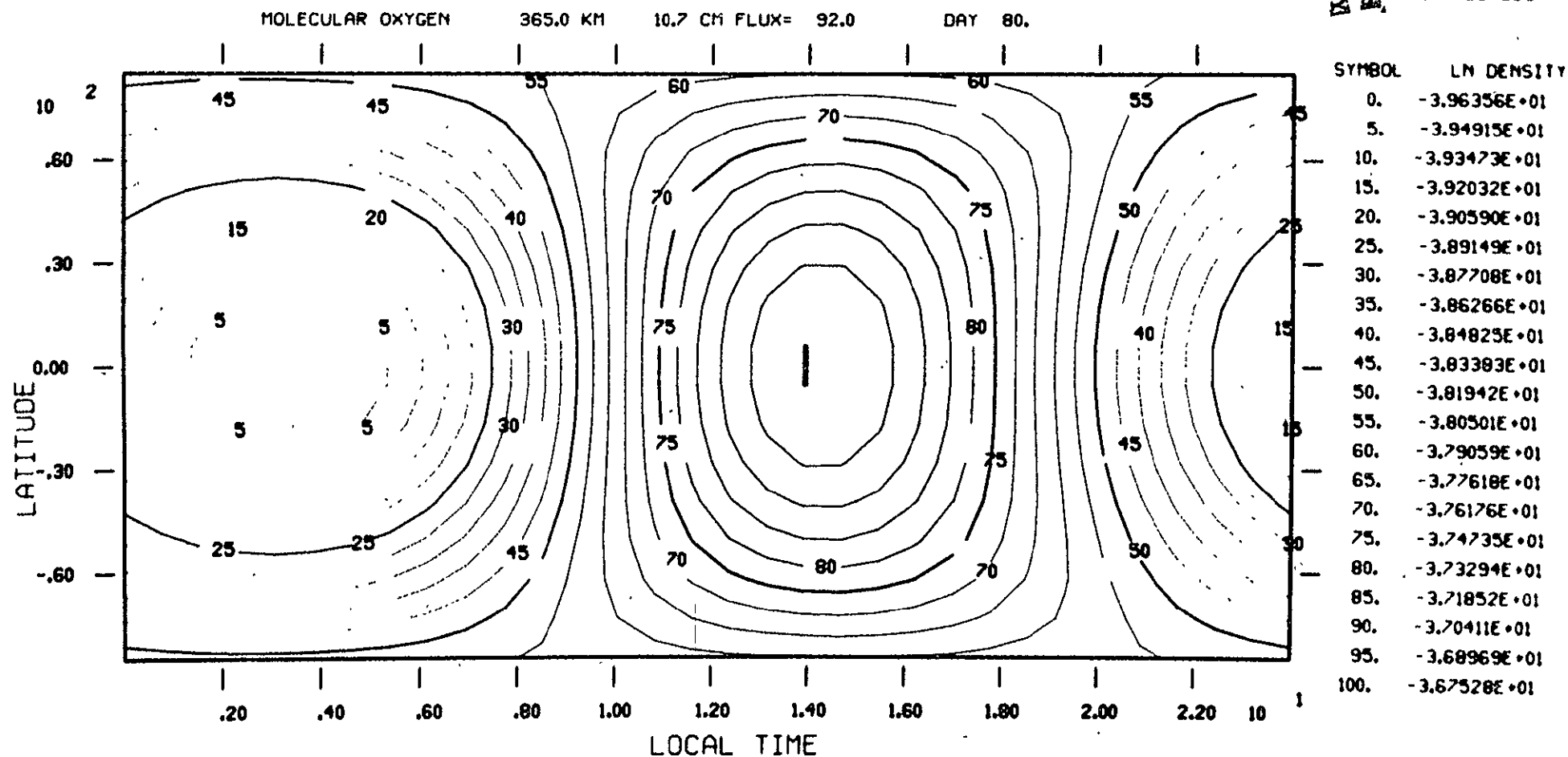


SYMBOL	LN DENSITY
0.	-3.45939E+01
5.	-3.45078E+01
10.	-3.44218E+01
15.	-3.43358E+01
20.	-3.42498E+01
25.	-3.41638E+01
30.	-3.40777E+01
35.	-3.39917E+01
40.	-3.39057E+01
45.	-3.38197E+01
50.	-3.37337E+01
55.	-3.36476E+01
60.	-3.35616E+01
65.	-3.34756E+01
70.	-3.33896E+01
75.	-3.33036E+01
80.	-3.32175E+01
85.	-3.31315E+01
90.	-3.30455E+01
95.	-3.29595E+01
100.	-3.28735E+01

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ATMOSPHERIC DENSITY



ATMOSPHERIC DENSITY

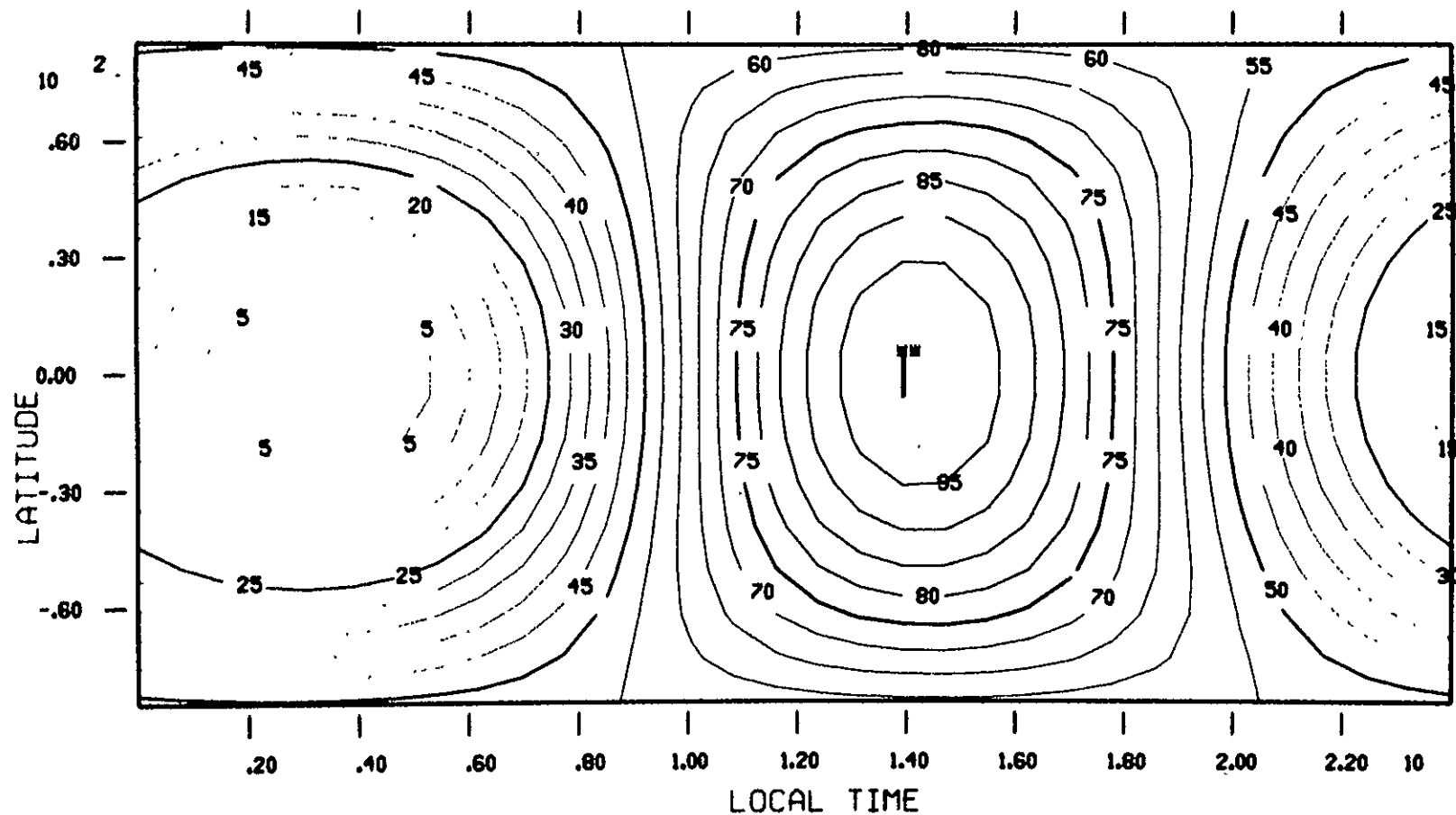
MOLECULAR OXYGEN

470.0 KM

10.7 CM FLUX= 92.0

DAY 80.

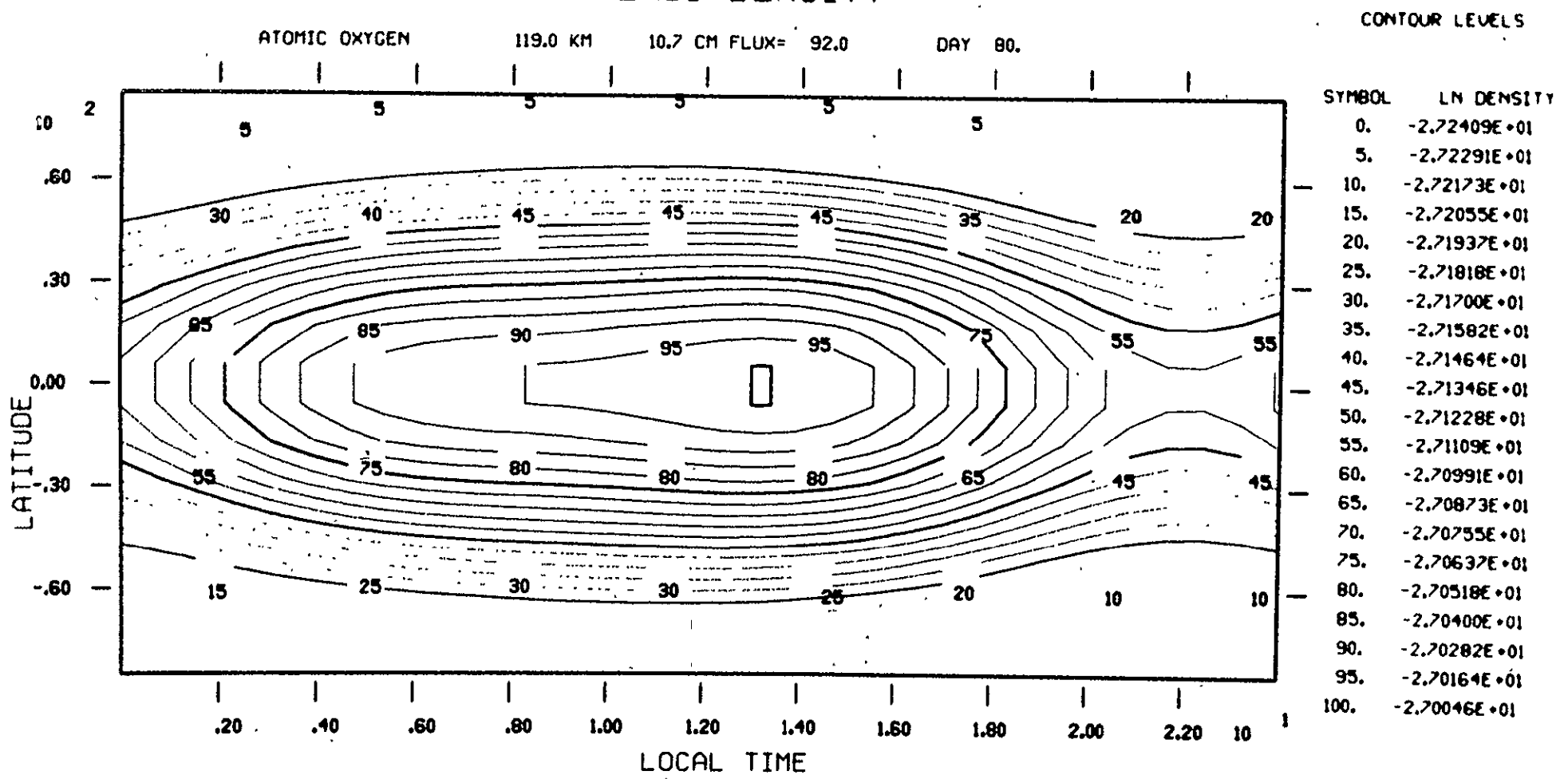
CONTOUR LEVELS



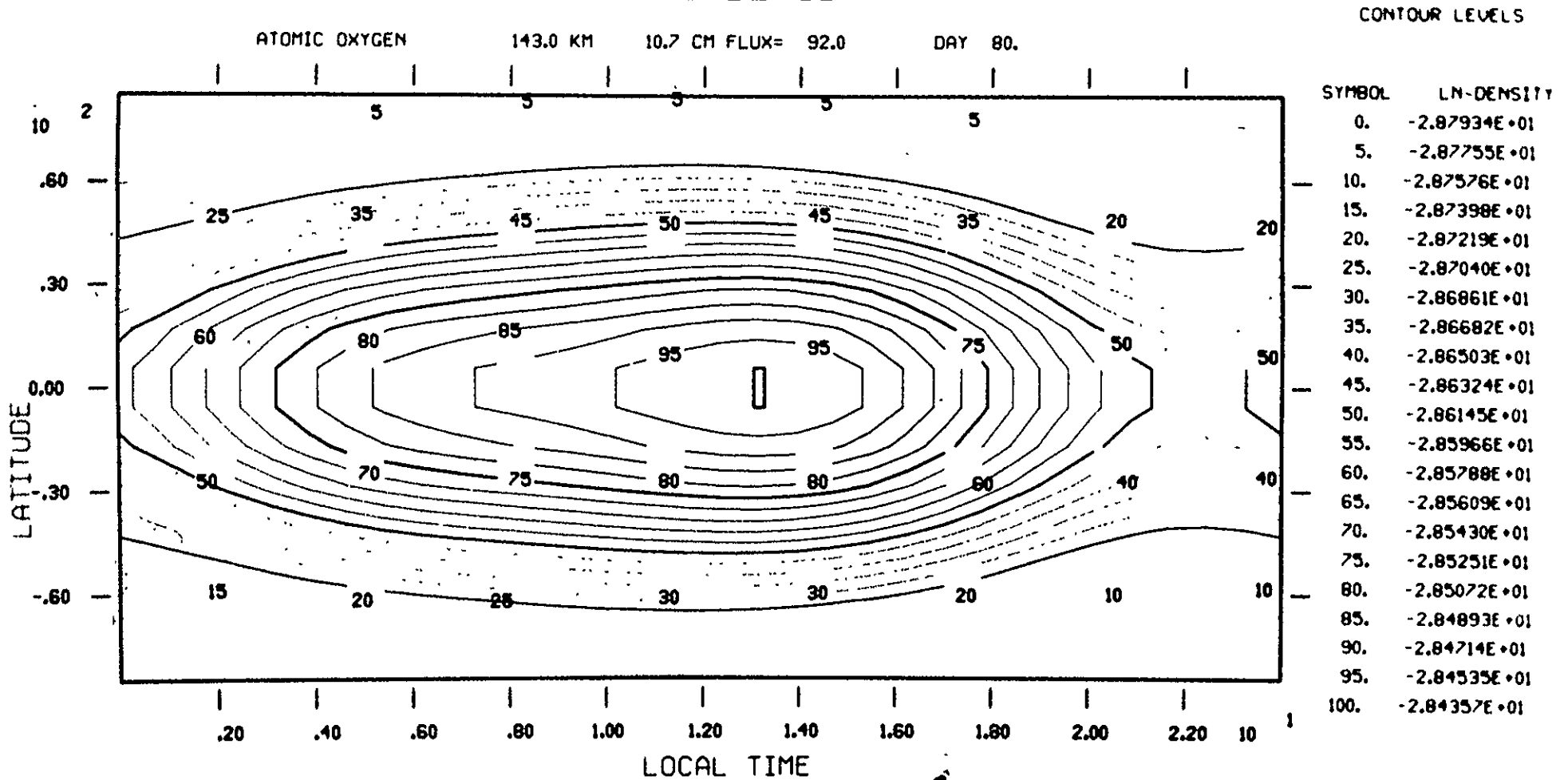
SYMBOL	LN DENSITY
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5.	-4.45134E+01
10.	-4.43167E+01
15.	-4.41199E+01
20.	-4.39232E+01
25.	-4.37265E+01
30.	-4.35298E+01
35.	-4.33330E+01
40.	-4.31363E+01
45.	-4.29396E+01
50.	-4.27429E+01
55.	-4.25462E+01
60.	-4.23494E+01
65.	-4.21527E+01
70.	-4.19560E+01
75.	-4.17593E+01
80.	-4.15625E+01
85.	-4.13658E+01
90.	-4.11691E+01
95.	-4.09724E+01
100.	-4.07757E+01

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ATMOSPHERIC DENSITY



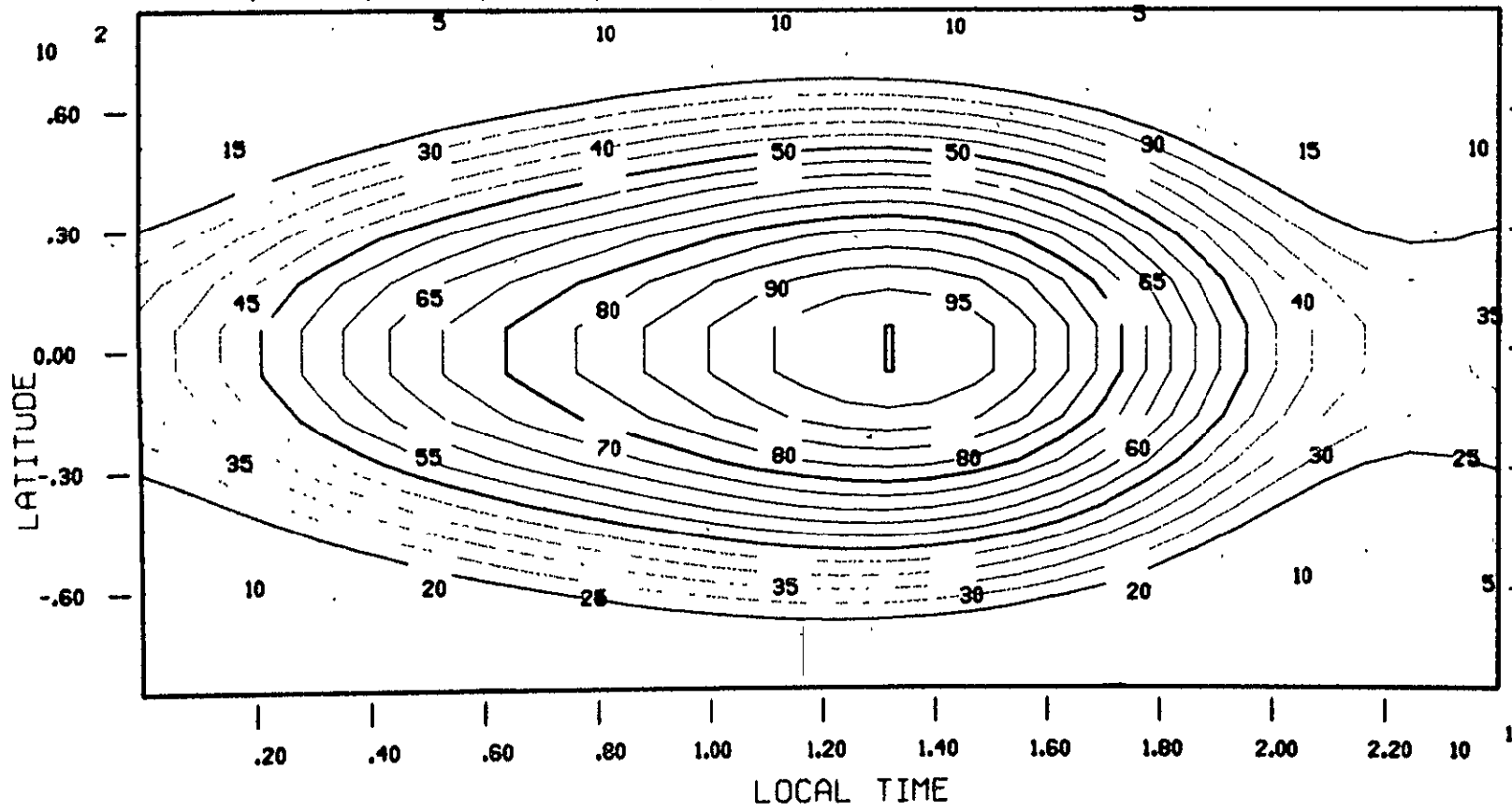
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CONTOUR LEVELS

ATOMIC OXYGEN 185.0 KM 10.7 CM FLUX= 92.0 DAY 80.



SYMBOL	LN DENSITY
0.	-3.07127E+01
5.	-3.06892E+01
10.	-3.06657E+01
15.	-3.06421E+01
20.	-3.06186E+01
25.	-3.05951E+01
30.	-3.05716E+01
35.	-3.05481E+01
40.	-3.05246E+01
45.	-3.05010E+01
50.	-3.04775E+01
55.	-3.04540E+01
60.	-3.04305E+01
65.	-3.04070E+01
70.	-3.03835E+01
75.	-3.03599E+01
80.	-3.03364E+01
85.	-3.03129E+01
90.	-3.02894E+01
95.	-3.02659E+01
100.	-3.02423E+01

ATMOSPHERIC DENSITY

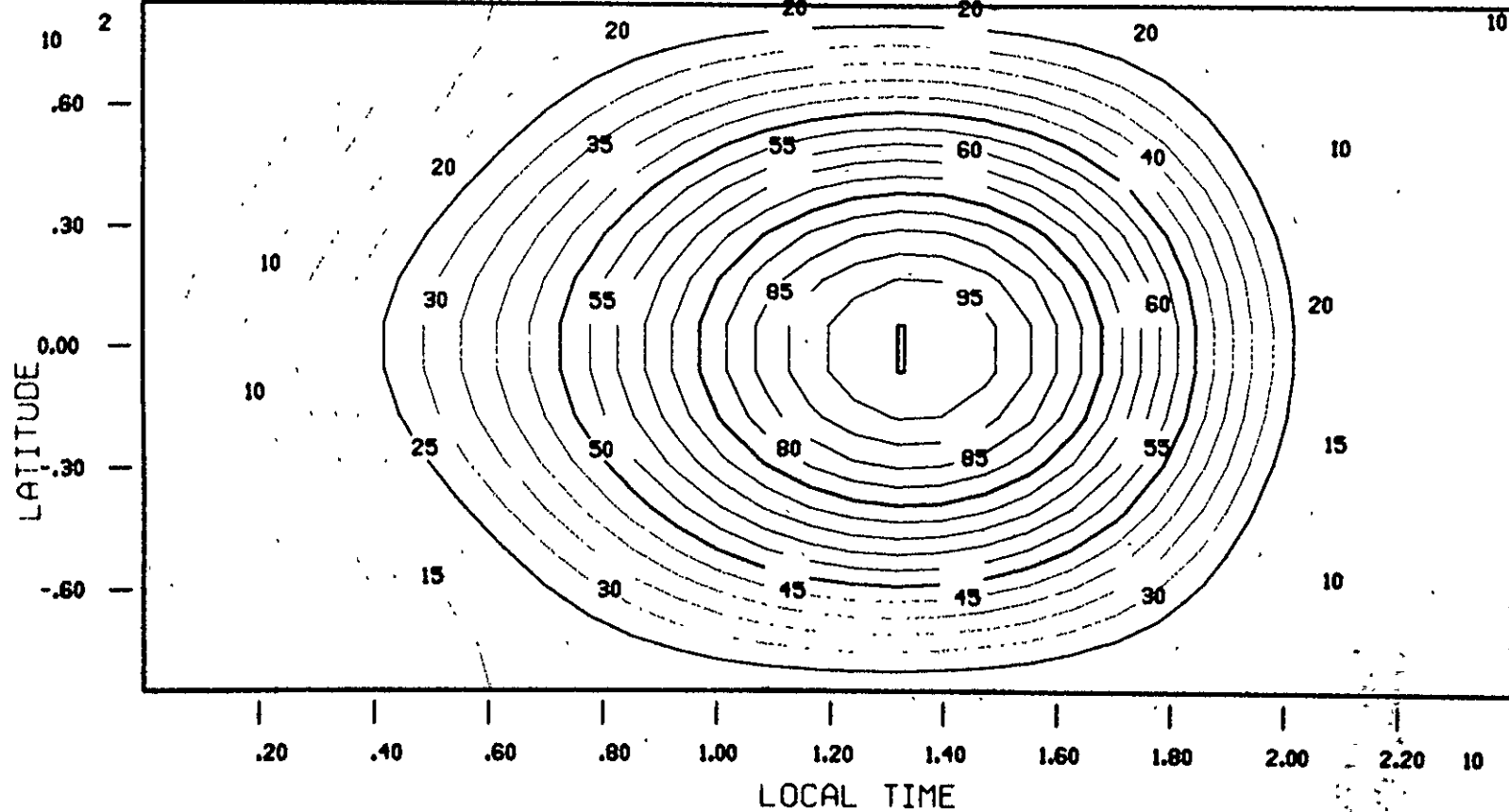
CONTOUR LEVELS

ATOMIC OXYGEN

260.0 KM

10.7 CM FLUX= 92.0

DAY 80.

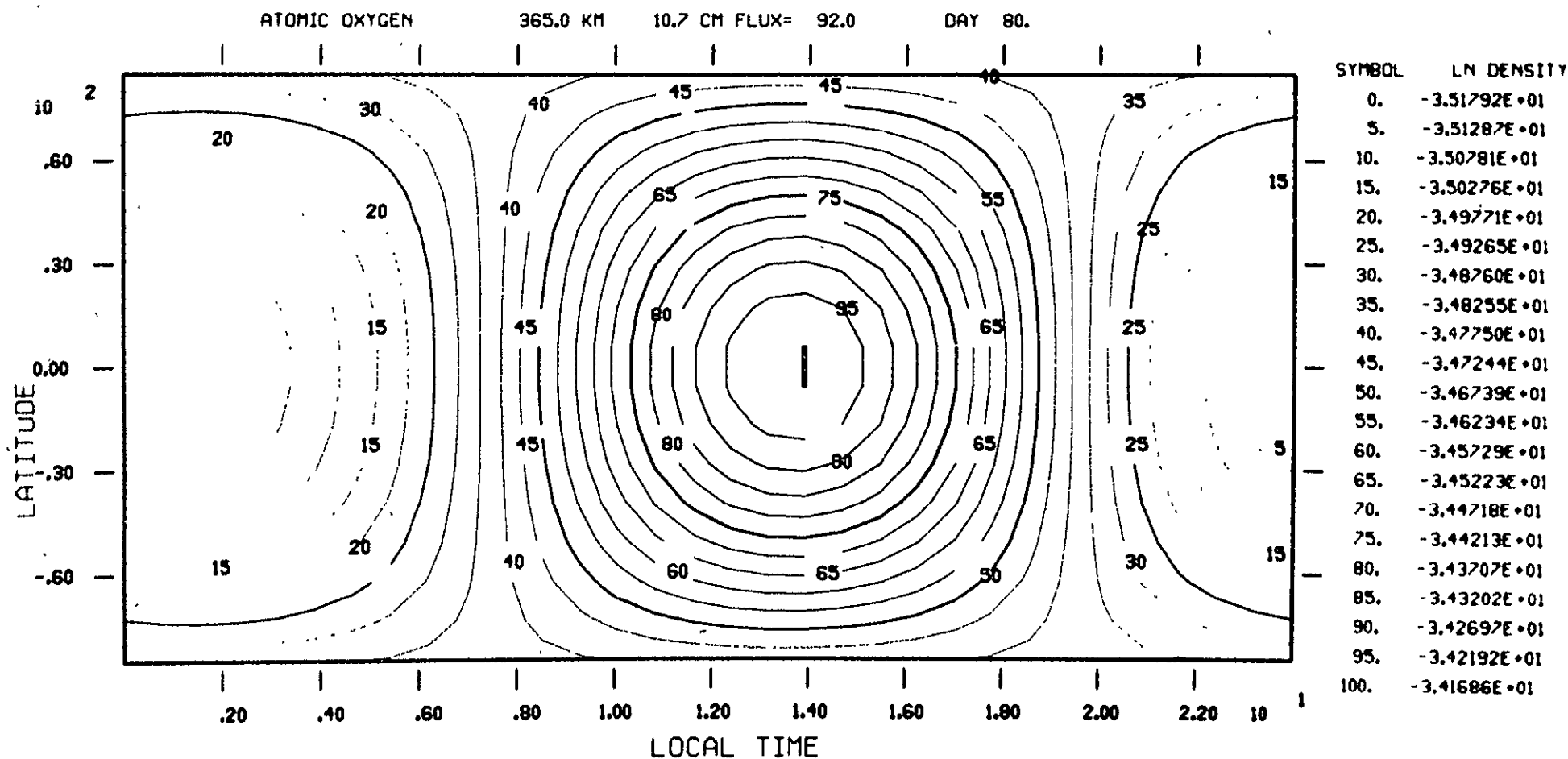


SYMBOL	LN DENSITY
0.	-3.27557E+01
5.	-3.27269E+01
10.	-3.26982E+01
15.	-3.26694E+01
20.	-3.26406E+01
25.	-3.26119E+01
30.	-3.25831E+01
35.	-3.25544E+01
40.	-3.25256E+01
45.	-3.24968E+01
50.	-3.24681E+01
55.	-3.24393E+01
60.	-3.24105E+01
65.	-3.23818E+01
70.	-3.23530E+01
75.	-3.23242E+01
80.	-3.22955E+01
85.	-3.22667E+01
90.	-3.22380E+01
95.	-3.22092E+01
100.	-3.21804E+01

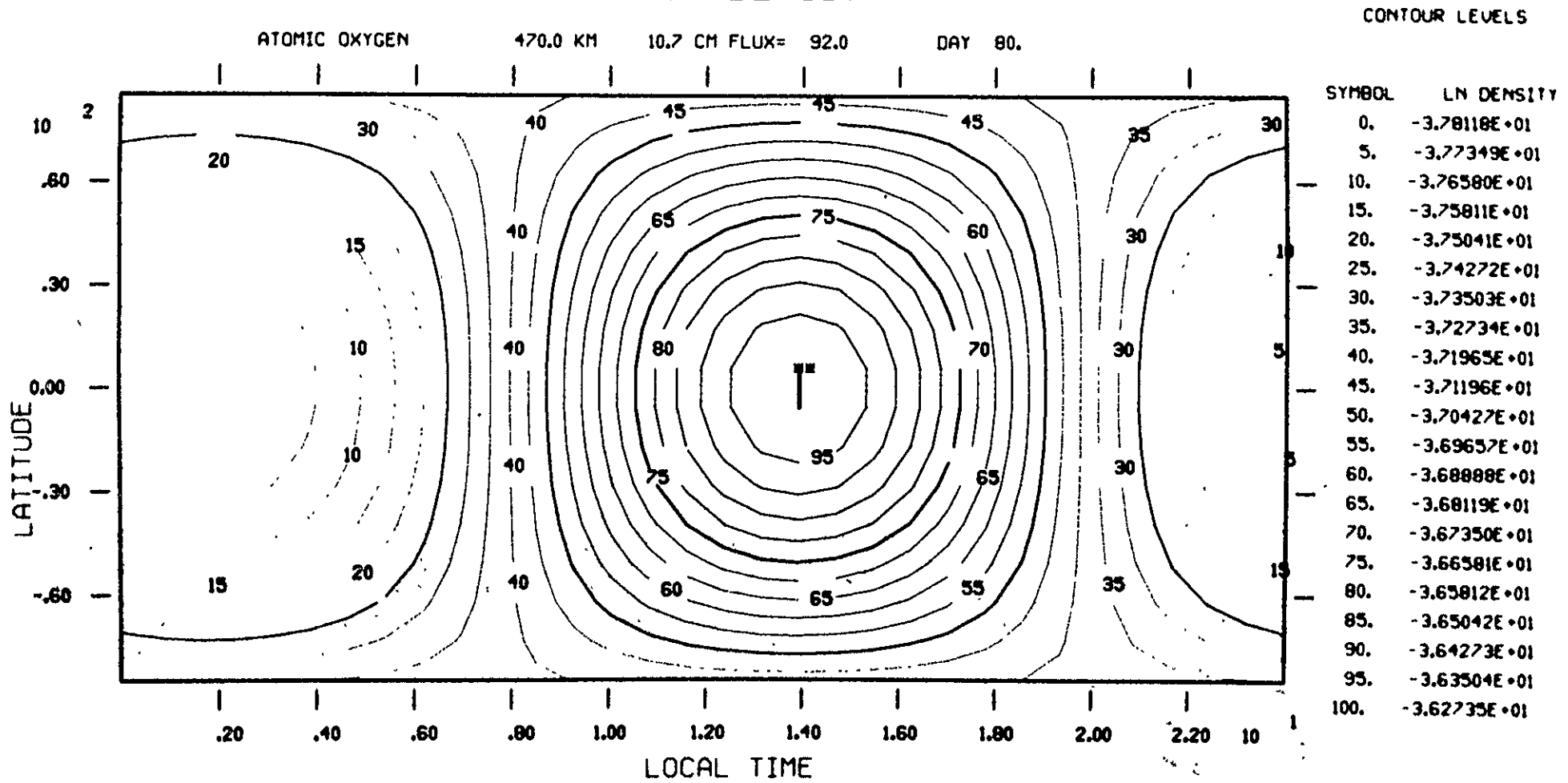
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ATMOSPHERIC DENSITY

CONTOUR LEVELS



ATMOSPHERIC DENSITY

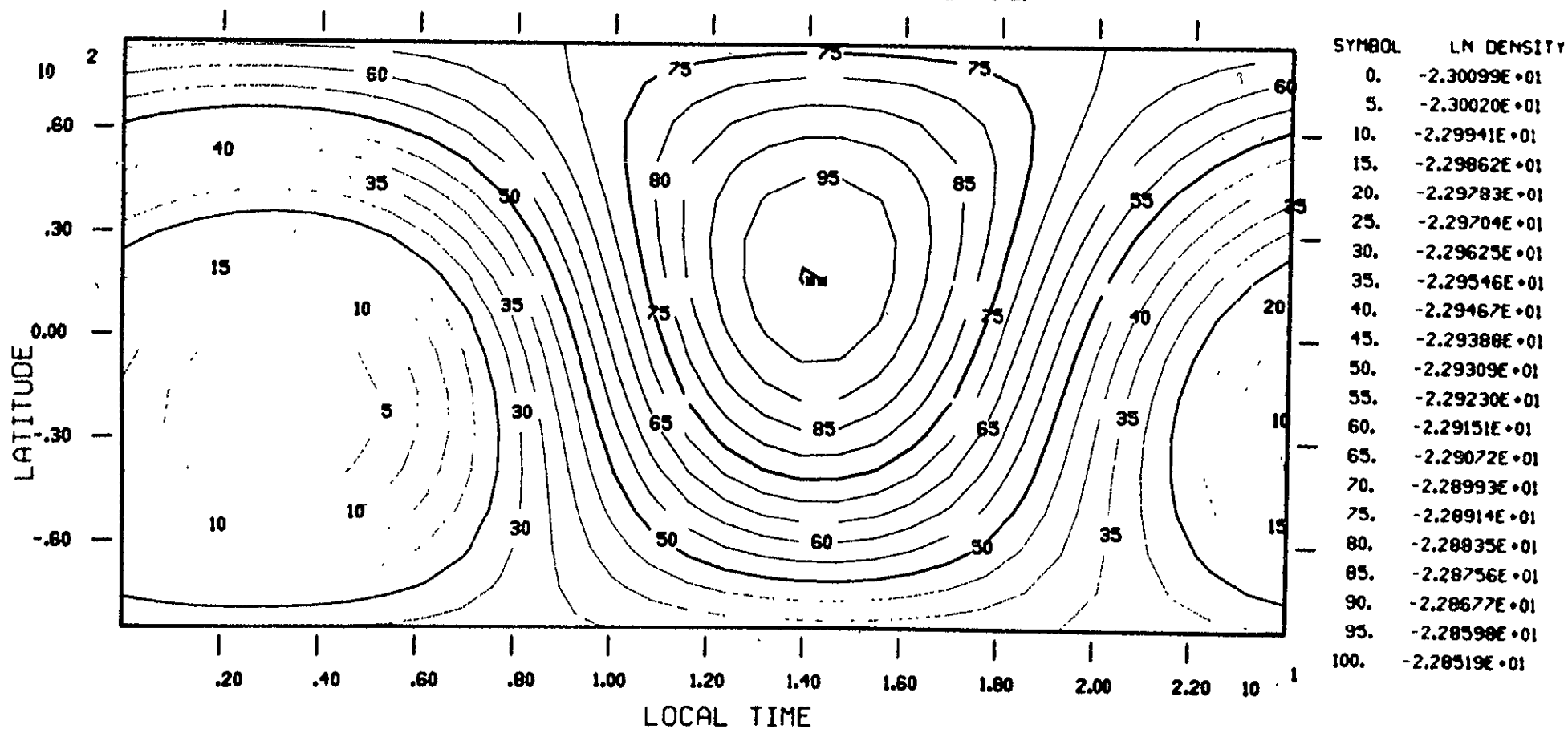


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ATMOSPHERIC DENSITY

MOLECULAR NITROGEN 119.0 KM 10.7 CM FLUX= 92.0 DAY 172.

CONTOUR LEVELS



ATMOSPHERIC DENSITY

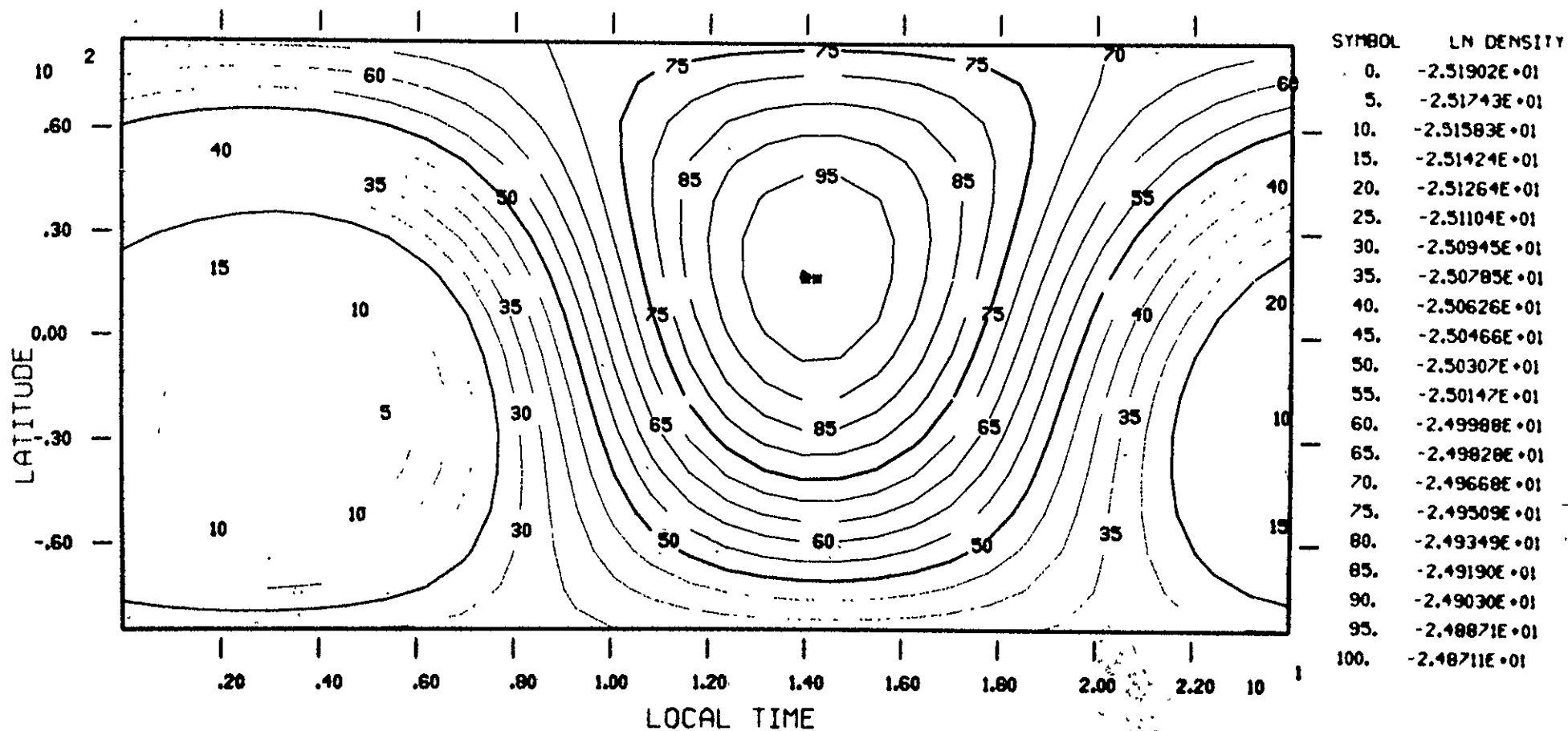
MOLECULAR NITROGEN

143.0 KM

10.7 CM FLUX= 92.0

DAY 172.

CONTOUR LEVELS

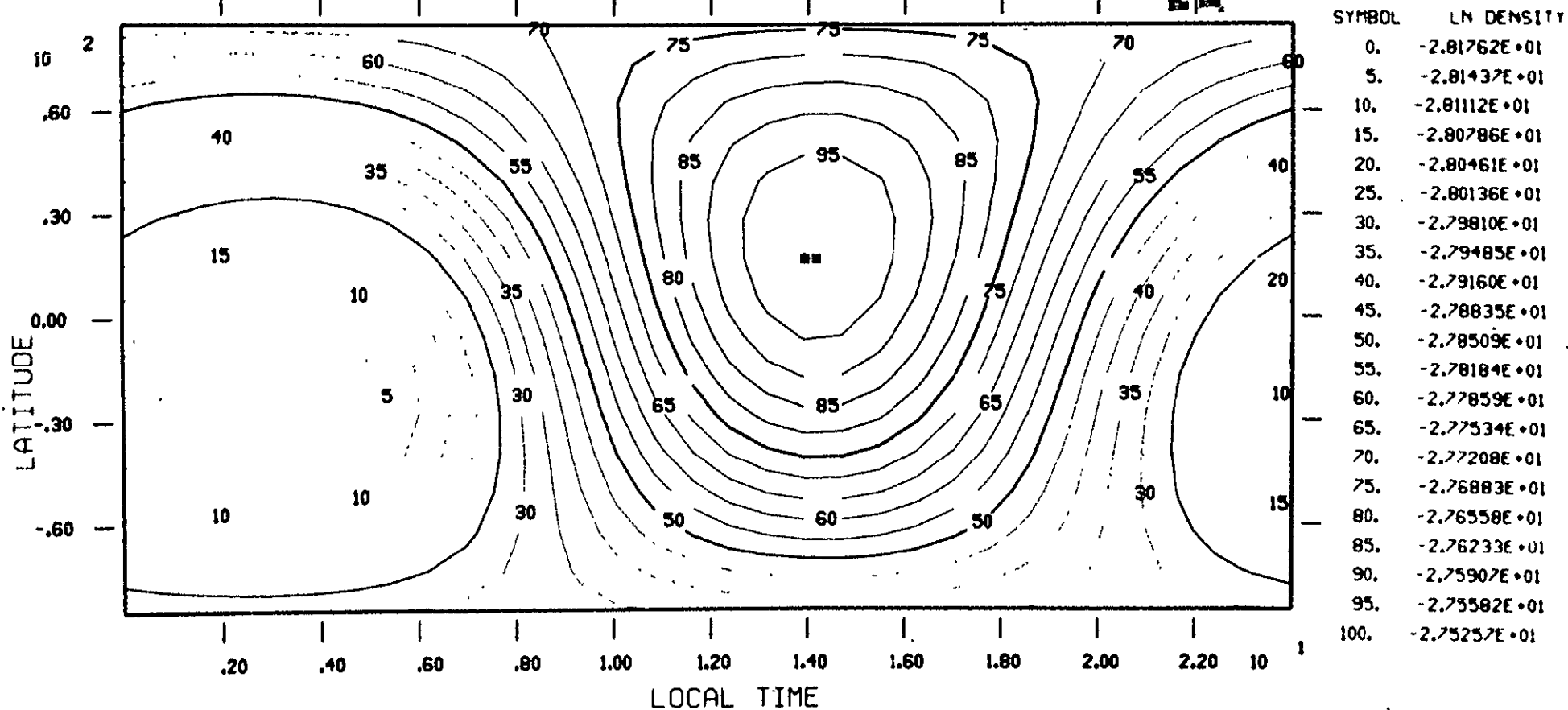


ATMOSPHERIC DENSITY

MOLECULAR NITROGEN 185.0 KM 10.7 CM FLUX= 92.0 DAY 172.

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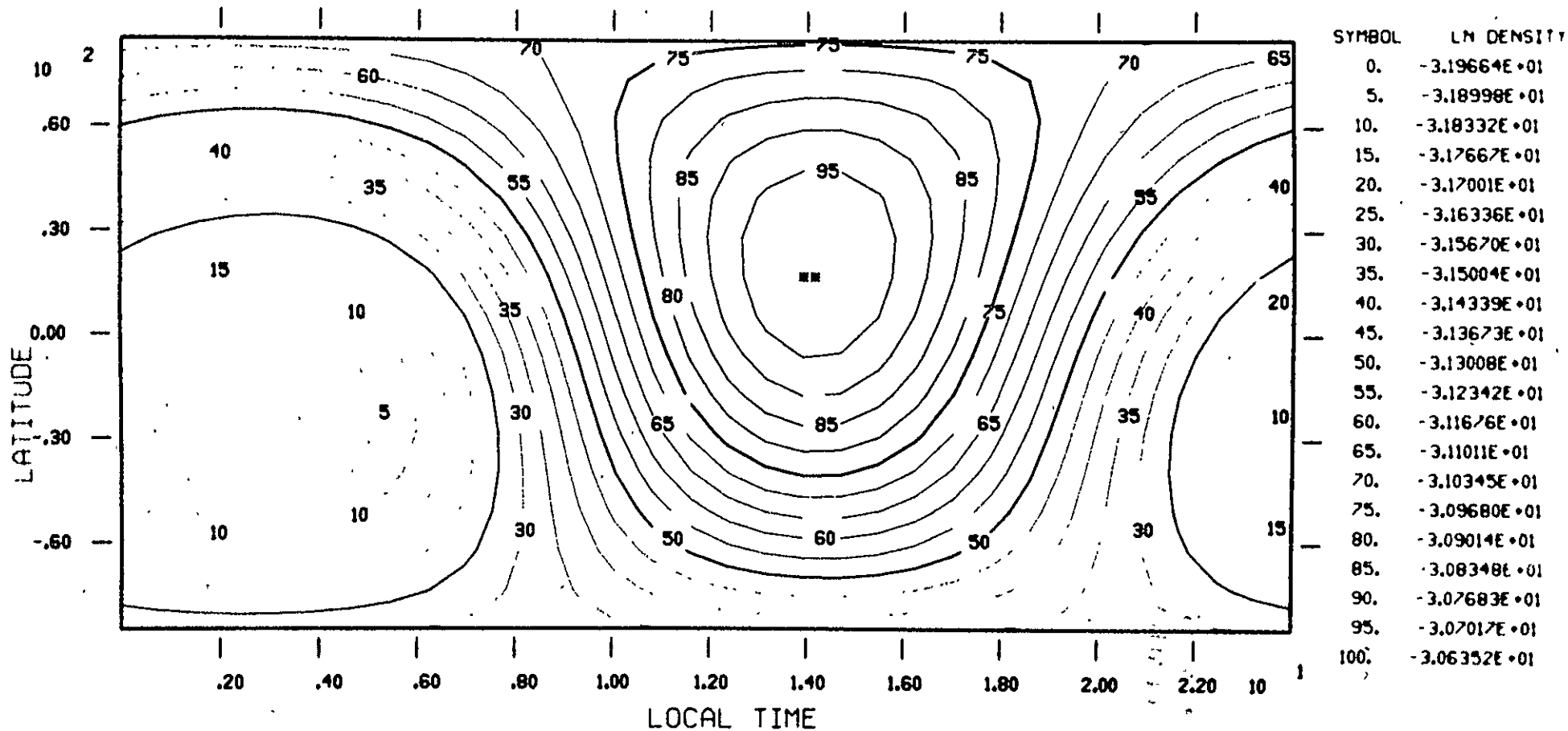
CONTOUR LEVELS



ATMOSPHERIC DENSITY

MOLECULAR NITROGEN 260.0 KM 10.7 CM FLUX= 92.0 DAY 172.

CONTOUR LEVELS

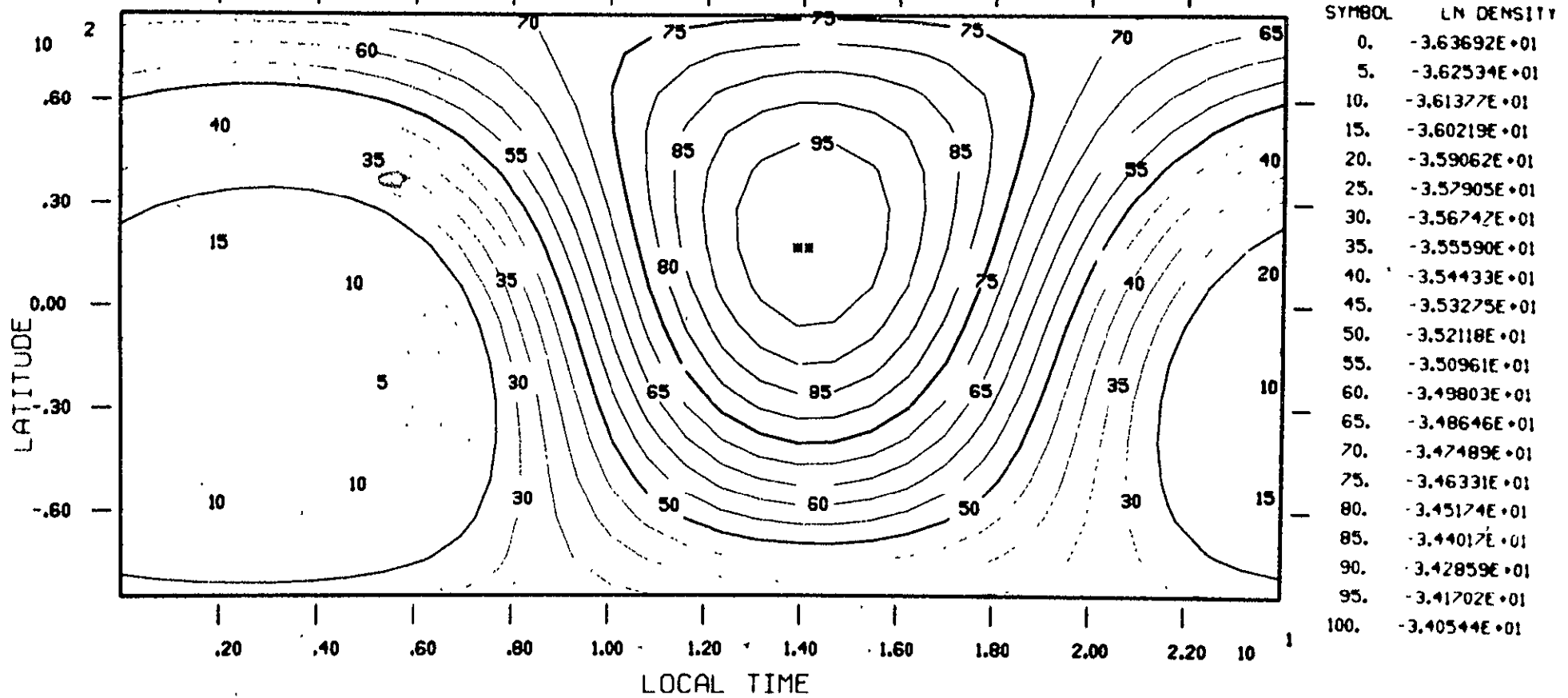


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ATMOSPHERIC DENSITY

MOLECULAR NITROGEN 365.0 KM 10.7 CM FLUX= 92.0 DAY 172.

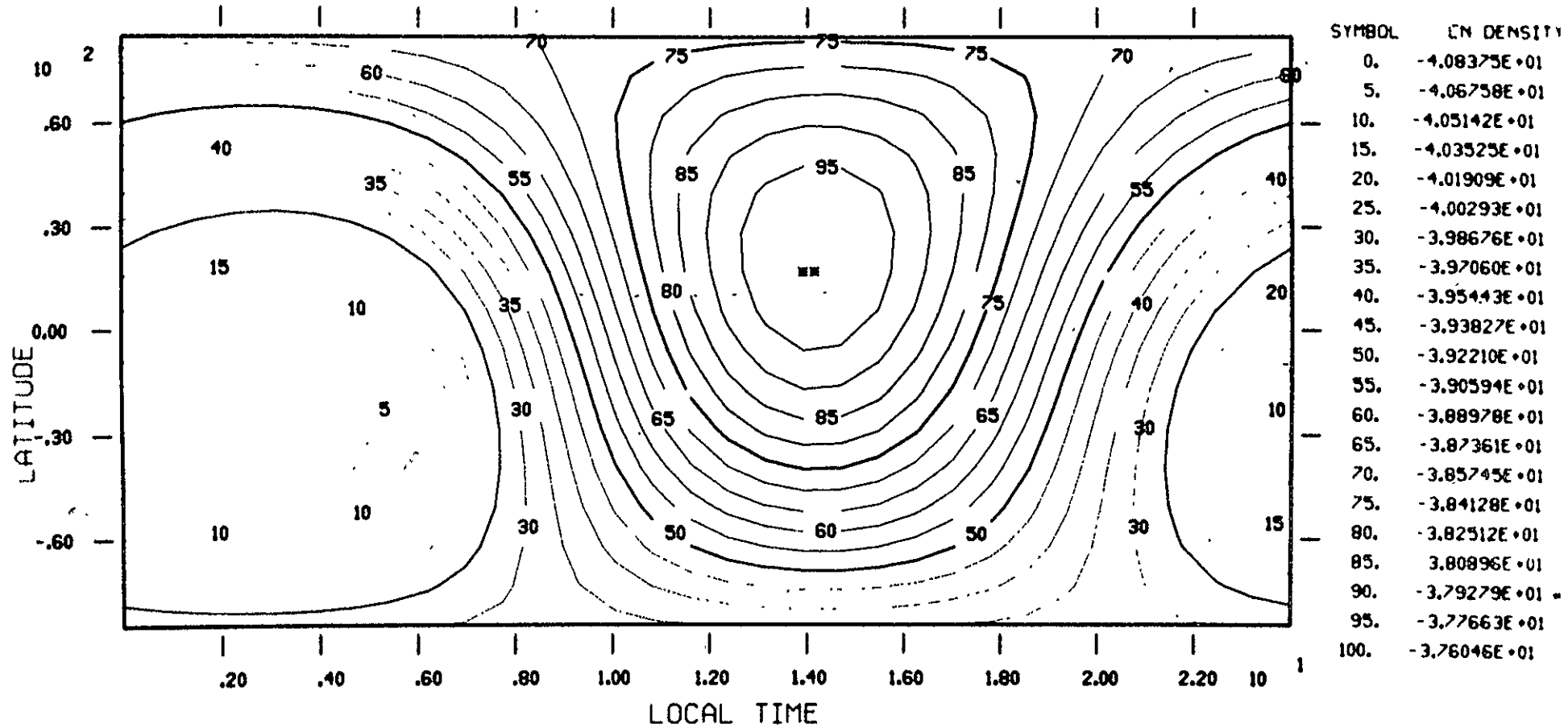
CONTOUR LEVELS



ATMOSPHERIC DENSITY

MOLECULAR NITROGEN 470.0 KM 10.7 CM FLUX= 92.0 DAY 172.

CONTOUR LEVELS

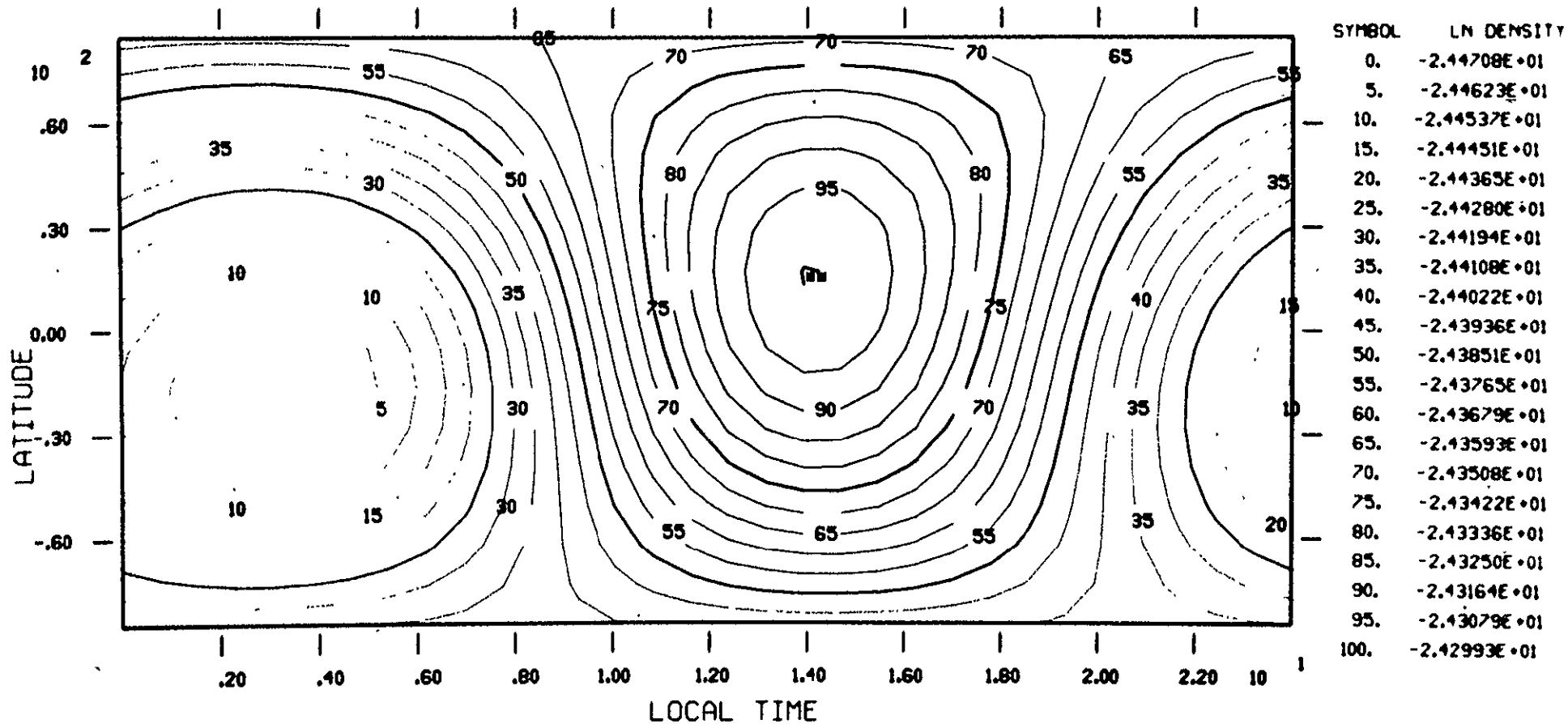


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ATMOSPHERIC DENSITY

CONTOUR LEVELS

MOLECULAR OXYGEN 119.0 KM 10.7 CM FLUX= 92.0 DAY 172.



ATMOSPHERIC DENSITY

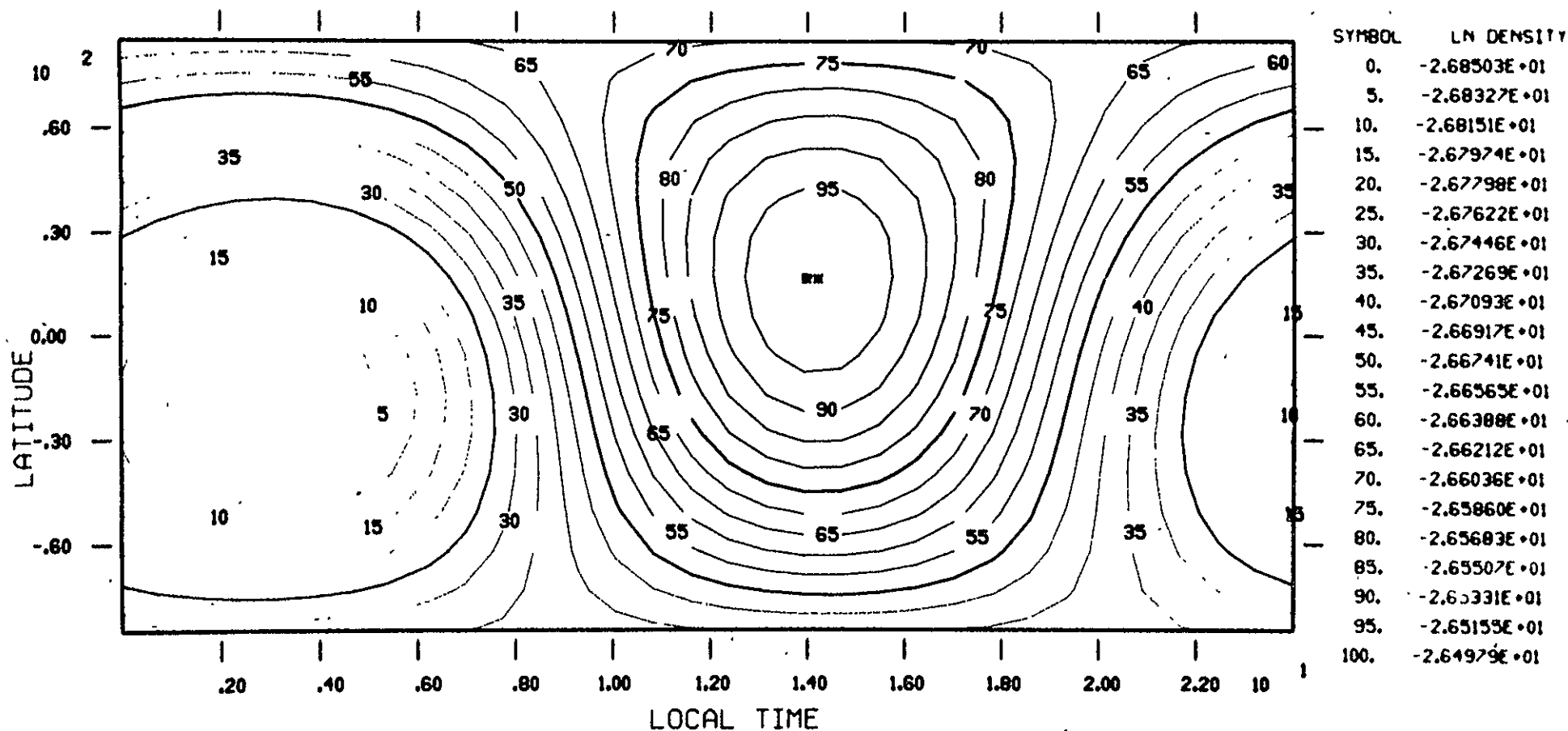
CONTOUR LEVELS

MOLECULAR OXYGEN

143.0 KM

10.7 CM FLUX= 92.0

DAY 172.



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ATMOSPHERIC DENSITY

MOLECULAR OXYGEN

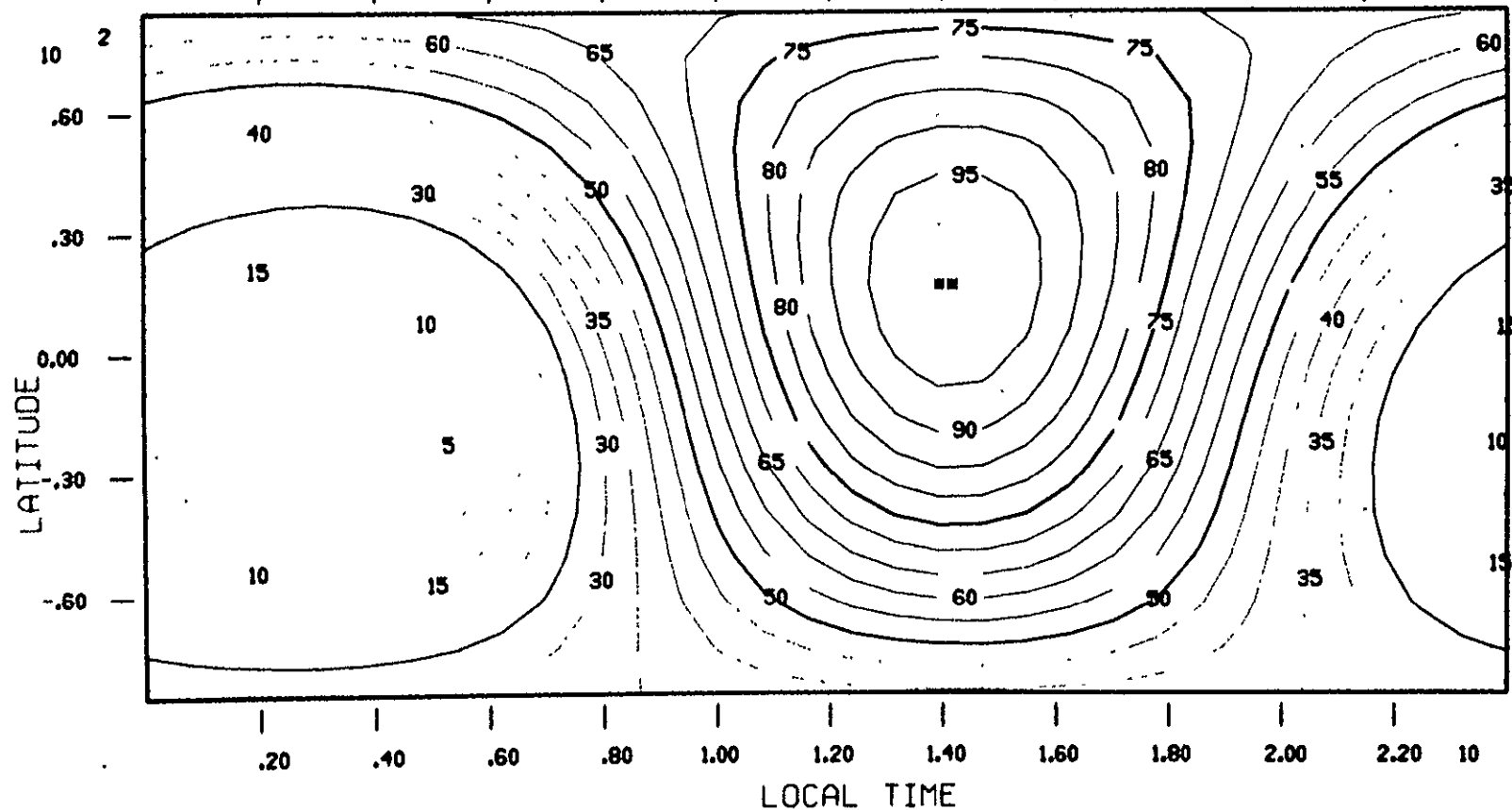
185.0 KM

10.7 CM FLUX= 92.0

DAY 172.

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CONTOUR LEVELS



SYMBOL	LN DENSITY
0.	-3.01601E+01
5.	-3.01236E+01
10.	-3.00870E+01
15.	-3.00505E+01
20.	-3.00139E+01
25.	-2.99774E+01
30.	-2.99408E+01
35.	-2.99043E+01
40.	-2.98677E+01
45.	-2.98312E+01
50.	-2.97946E+01
55.	-2.97581E+01
60.	-2.97215E+01
65.	-2.96850E+01
70.	-2.96484E+01
75.	-2.96119E+01
80.	-2.95753E+01
85.	-2.95388E+01
90.	-2.95023E+01
95.	-2.94657E+01
100.	-2.94292E+01

ATMOSPHERIC DENSITY

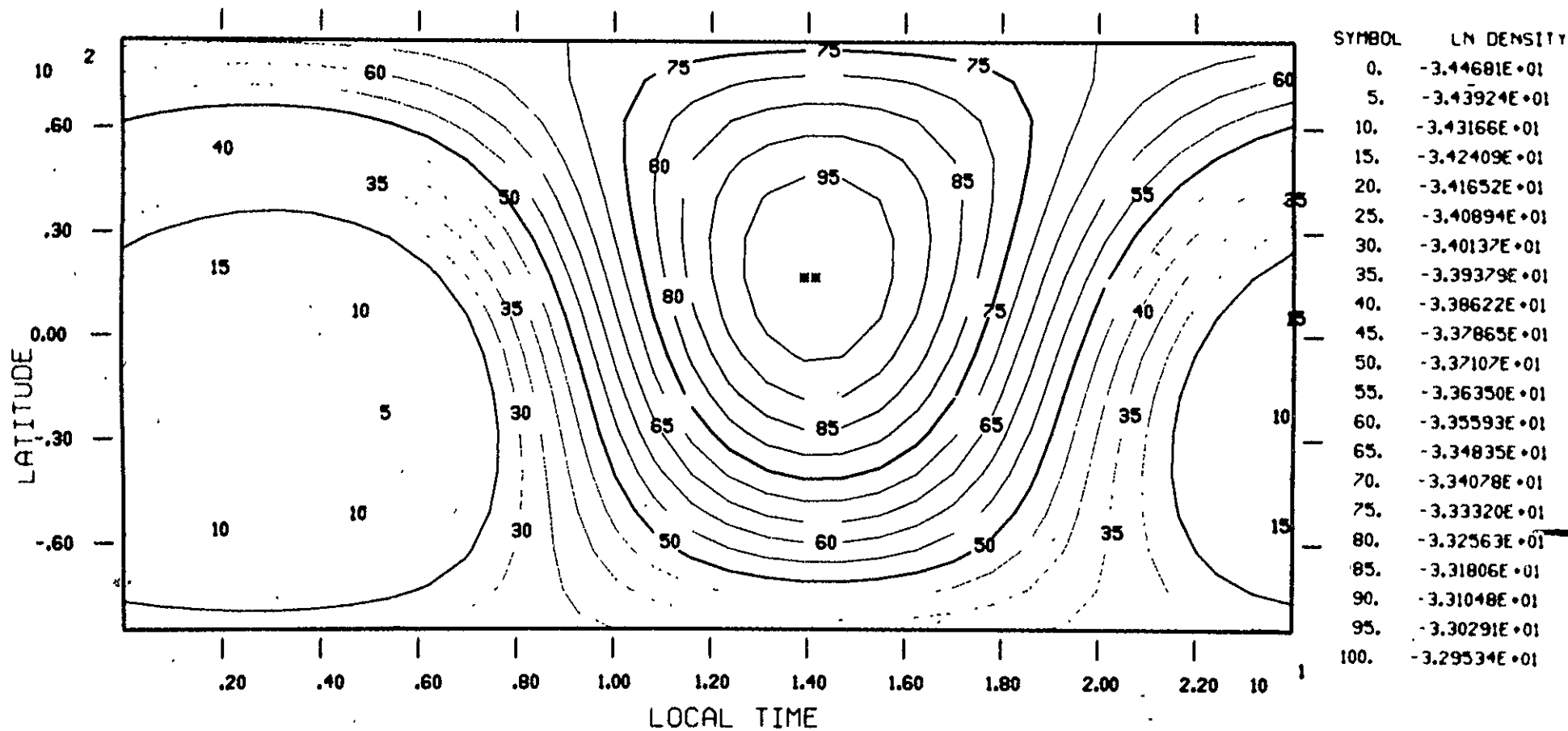
MOLECULAR OXYGEN

260.0 KM

10.7 CM FLUX= 92.0

DAY 172.

CONTOUR LEVELS

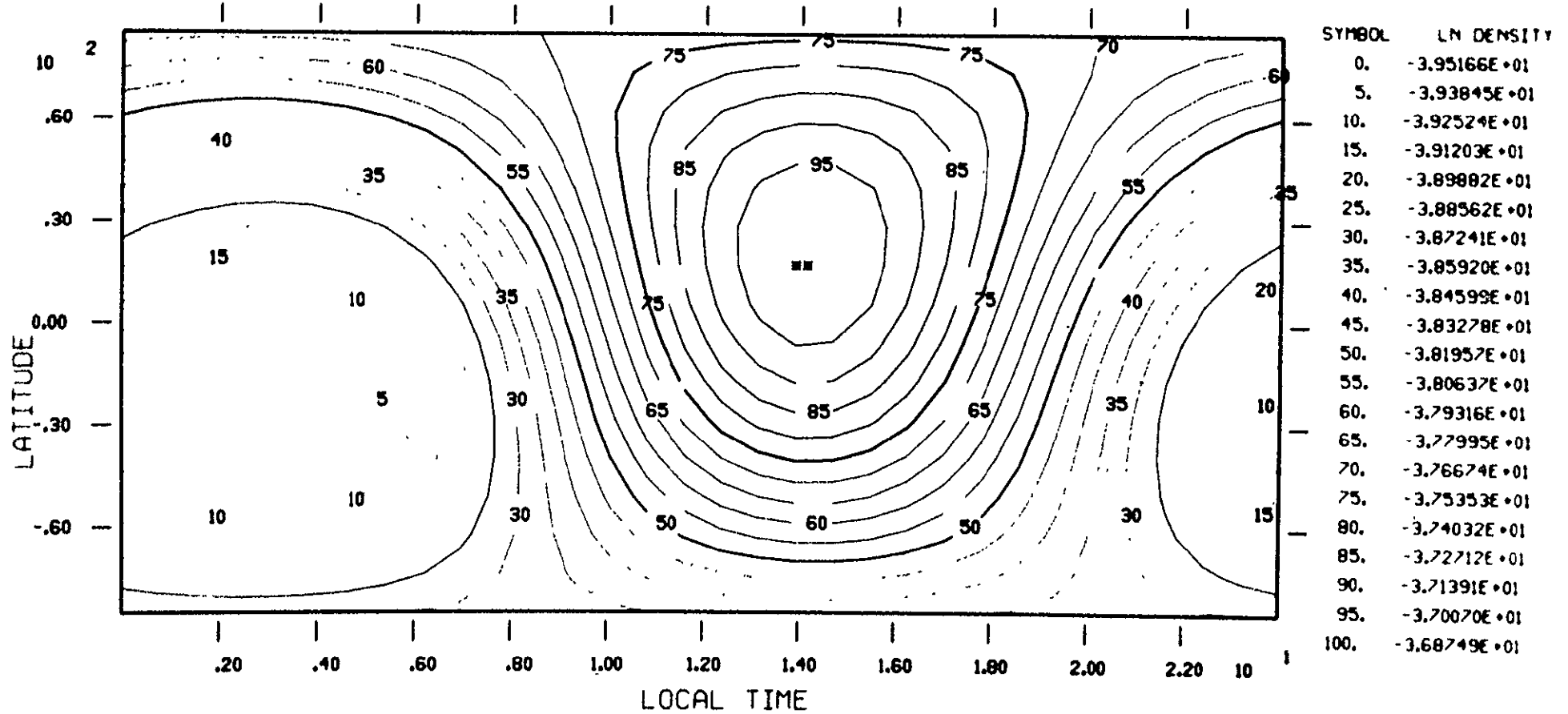


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ATMOSPHERIC DENSITY

MOLECULAR OXYGEN 365.0 KM 10.7 CM FLUX= 92.0 DAY 172.

CONTOUR LEVELS



ATMOSPHERIC DENSITY

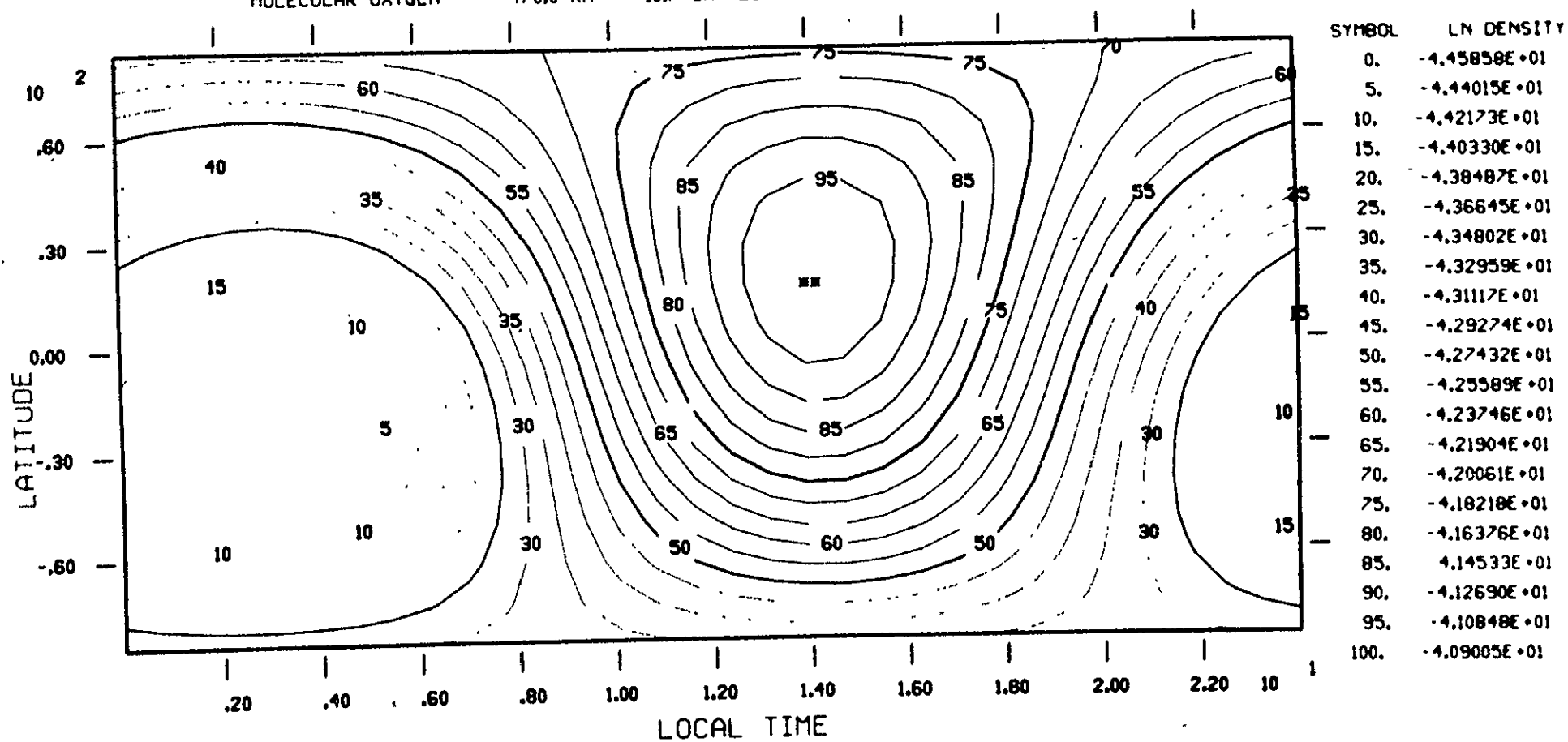
CONTOUR LEVELS

MOLECULAR OXYGEN

470.0 KM

10.7 CM FLUX= 92.0

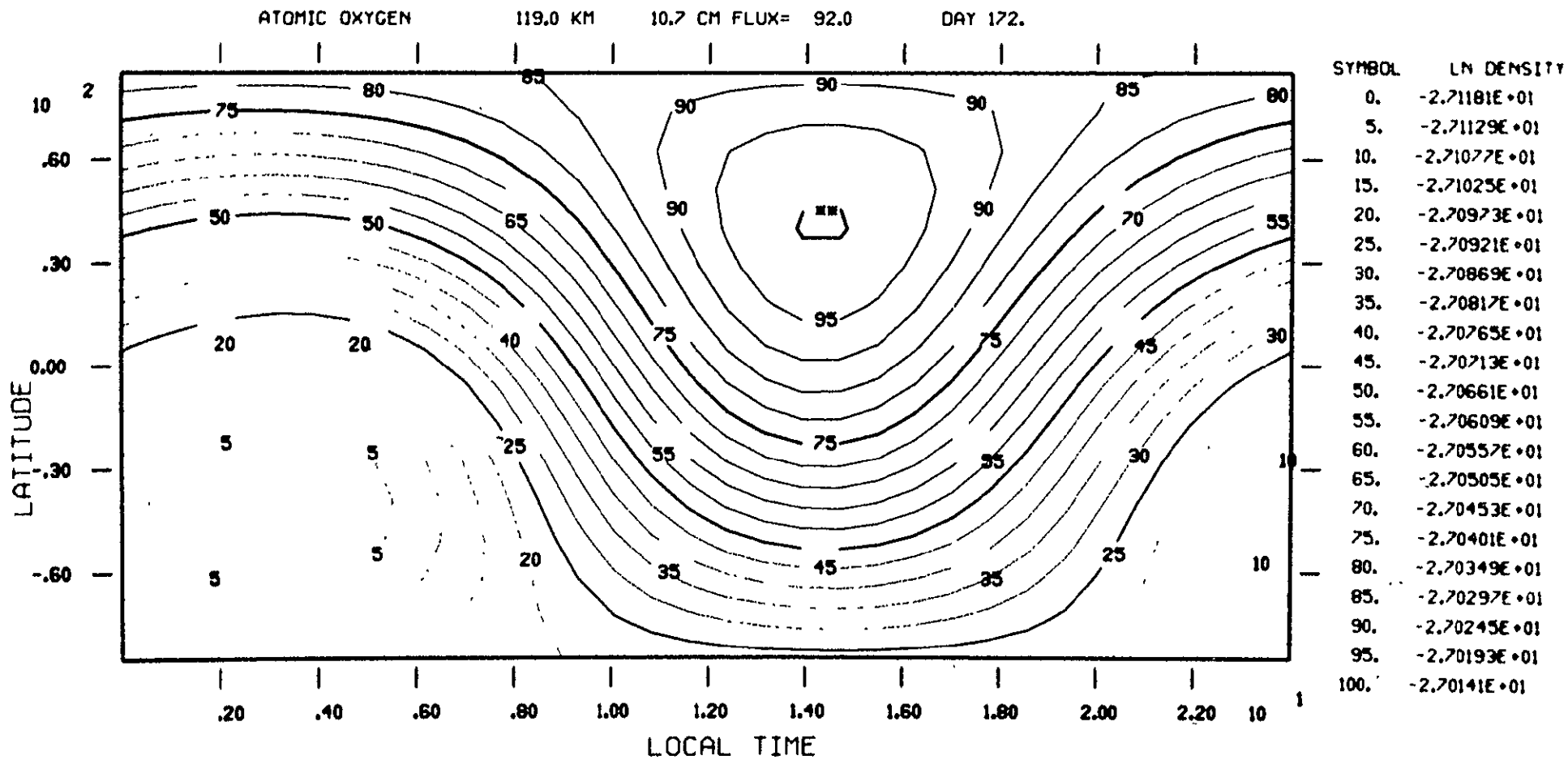
DAY 172.



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ATMOSPHERIC DENSITY

CONTOUR LEVELS



ATMOSPHERIC DENSITY

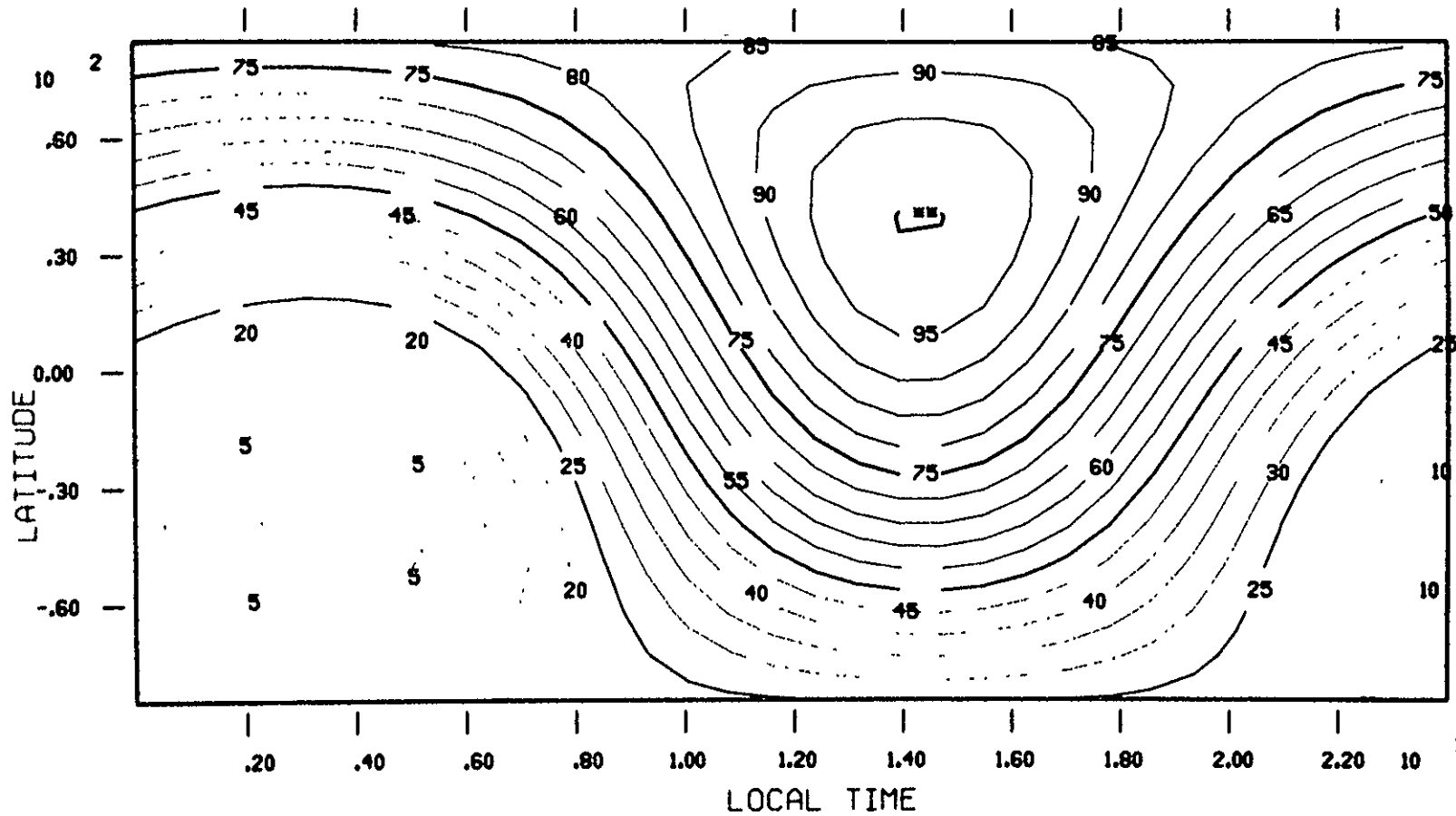
CONTOUR LEVELS

ATOMIC OXYGEN

143.0 KM

10.7 CM FLUX= 92.0

DAY 172.



SYMBOL LN DENSITY

0.	-2.86360E+01
5.	-2.86261E+01
10.	-2.86162E+01
15.	-2.86064E+01
20.	-2.85965E+01
25.	-2.85866E+01
30.	-2.85767E+01
35.	-2.85669E+01
40.	-2.85570E+01
45.	-2.85471E+01
50.	-2.85372E+01
55.	-2.85273E+01
60.	-2.85175E+01
65.	-2.85076E+01
70.	-2.84977E+01
75.	-2.84878E+01
80.	-2.84779E+01
85.	-2.84681E+01
90.	-2.84582E+01
95.	-2.84483E+01
100.	-2.84384E+01

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ATMOSPHERIC DENSITY

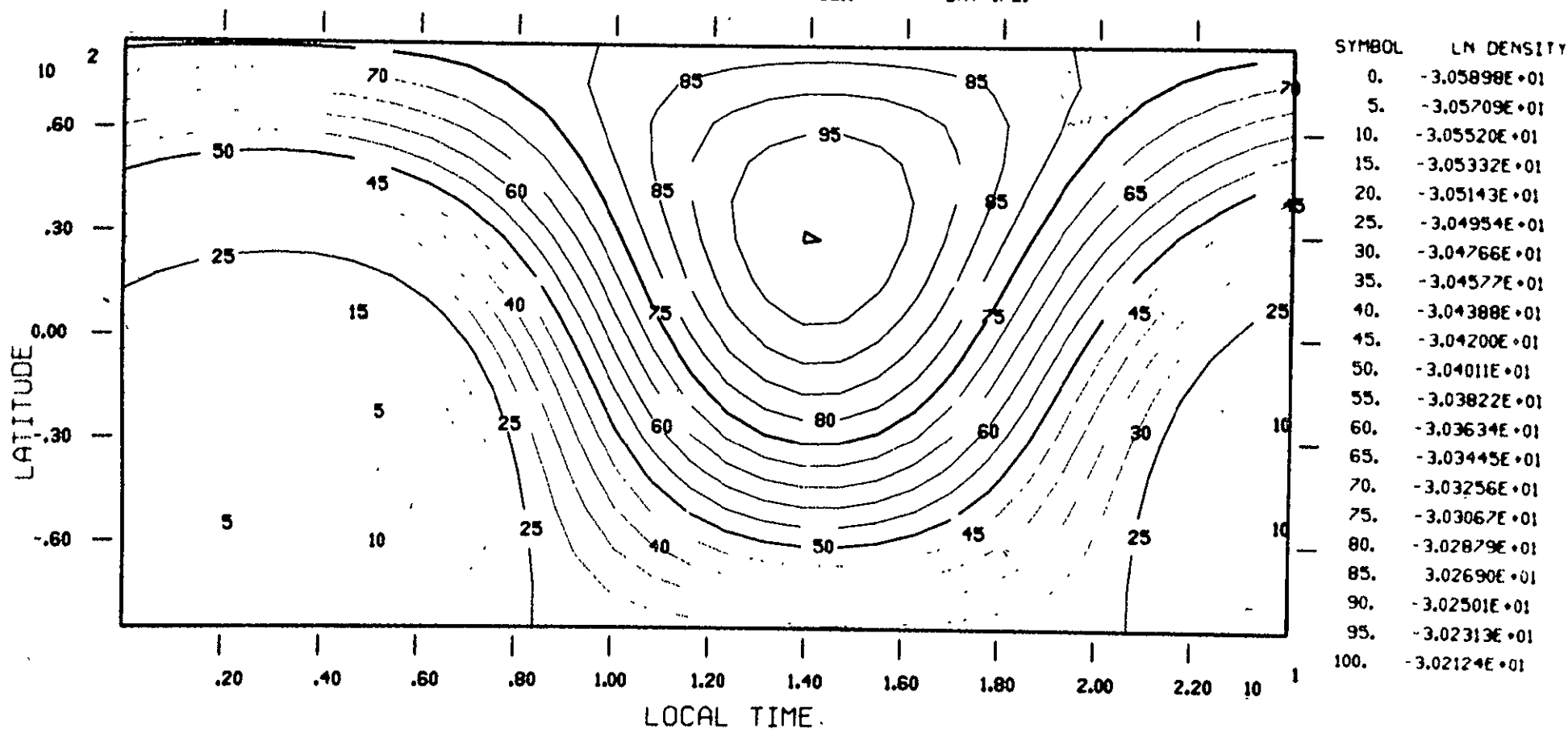
ATOMIC OXYGEN

185.0 KM

10.7 CM FLUX= 92.0

DAY 172.

CONTOUR LEVELS



ATMOSPHERIC DENSITY

CONTOUR LEVELS

ATOMIC OXYGEN

260.0 KM

10.7 CM FLUX= 92.0

DAY 172.

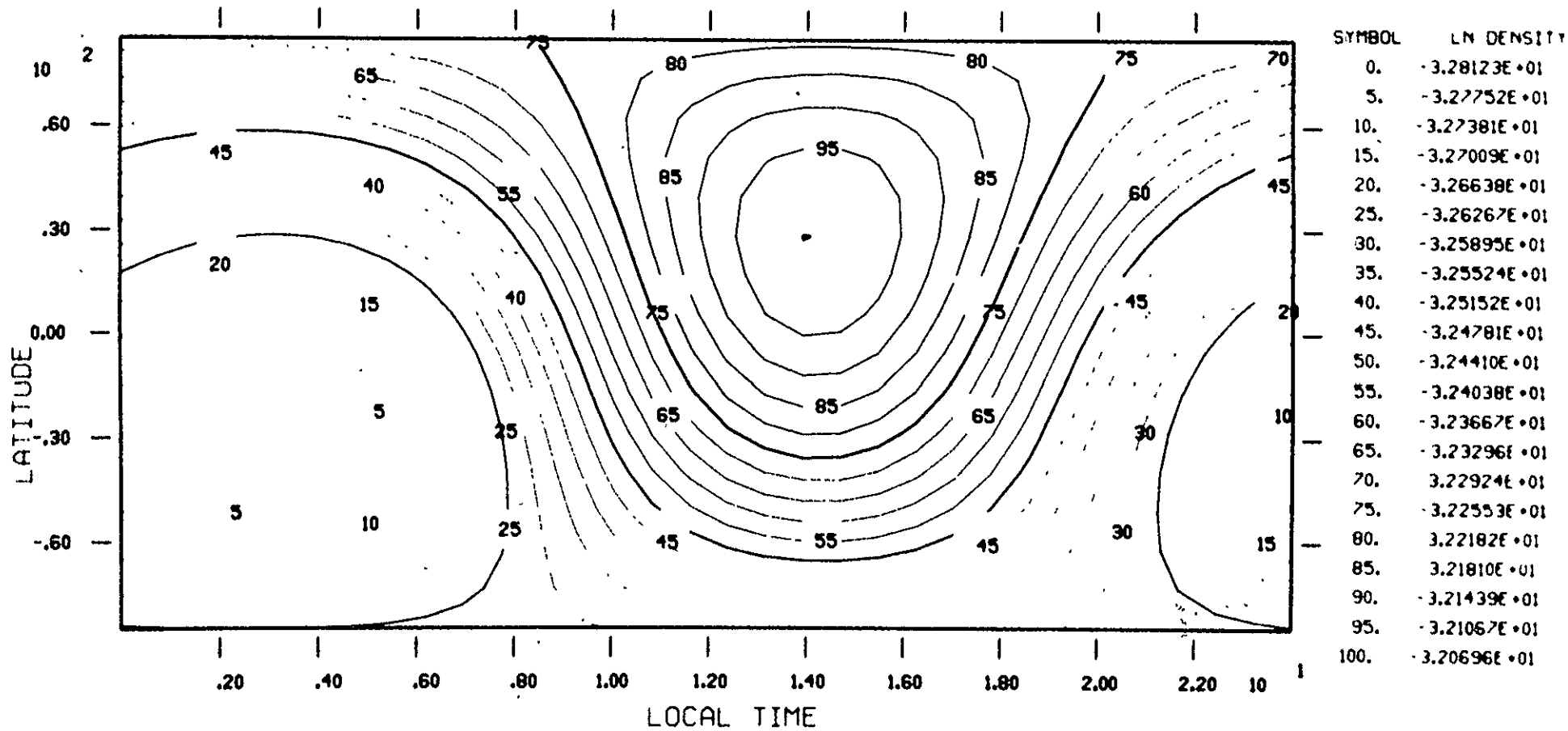


Fig
121

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ATMOSPHERIC DENSITY

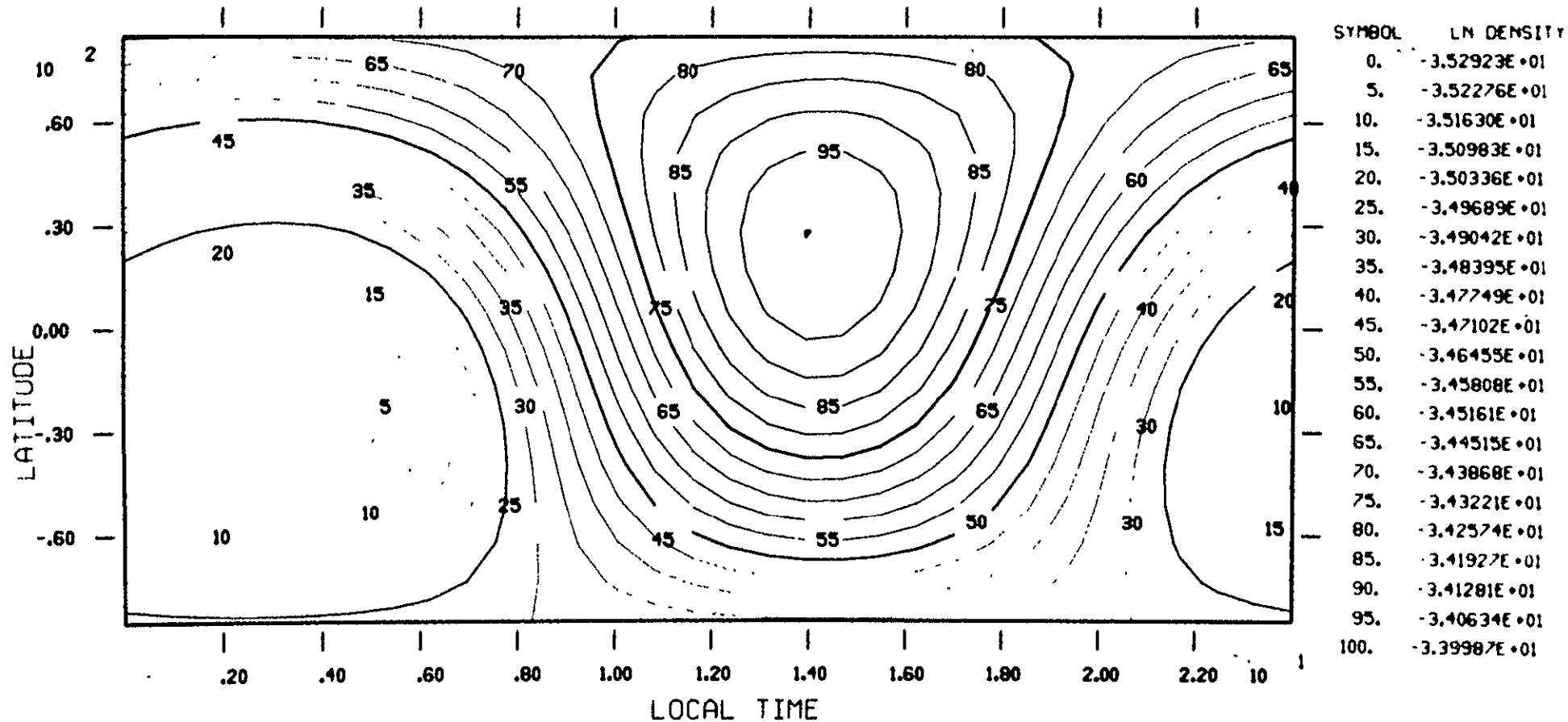
CONTOUR LEVELS

ATOMIC OXYGEN

365.0 KM

10.7 CM FLUX= 92.0

DAY 172.



ATMOSPHERIC DENSITY

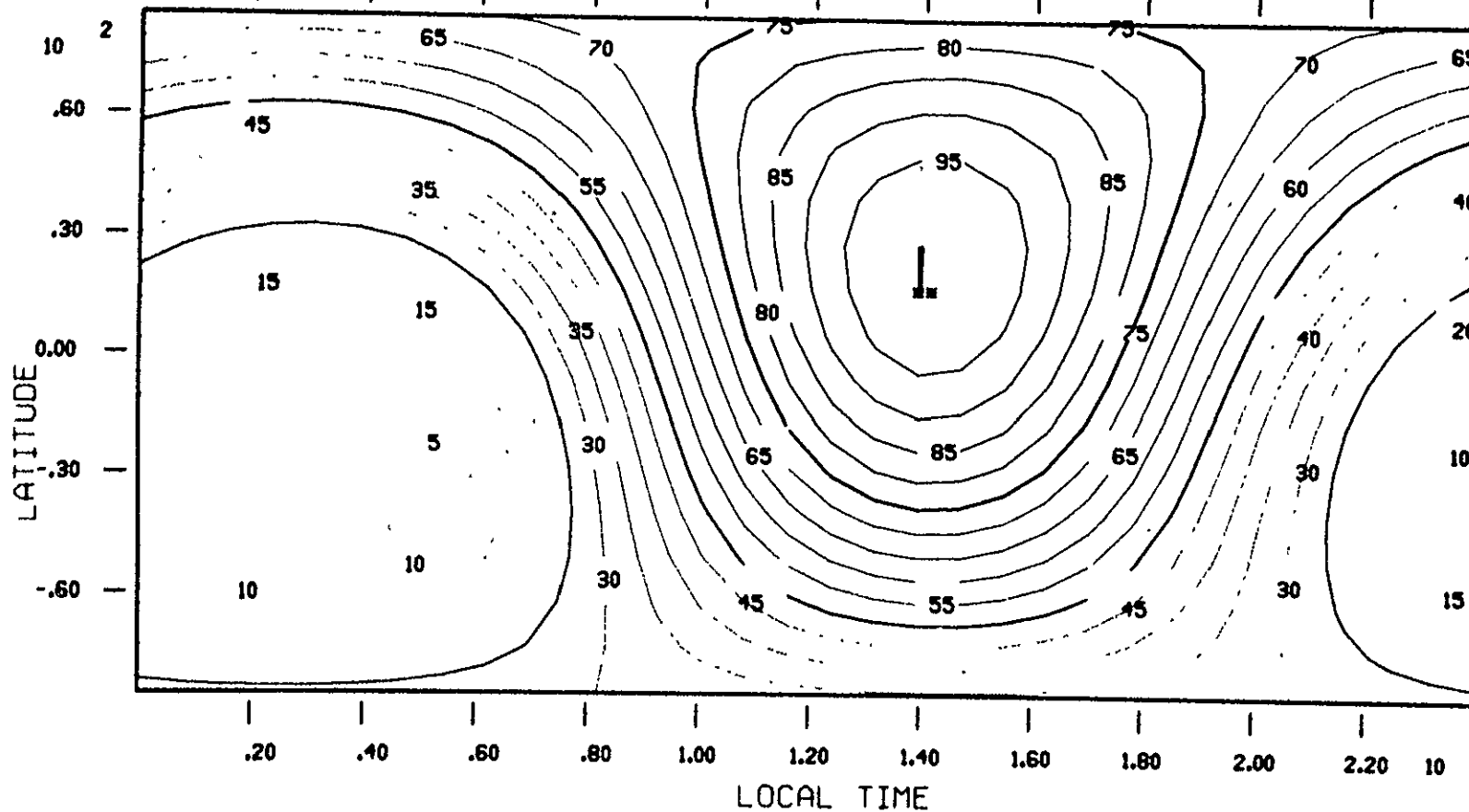
ATOMIC OXYGEN

470.0 KM

10.7 CM FLUX= 92.0

DAY 172.

CONTOUR LEVELS



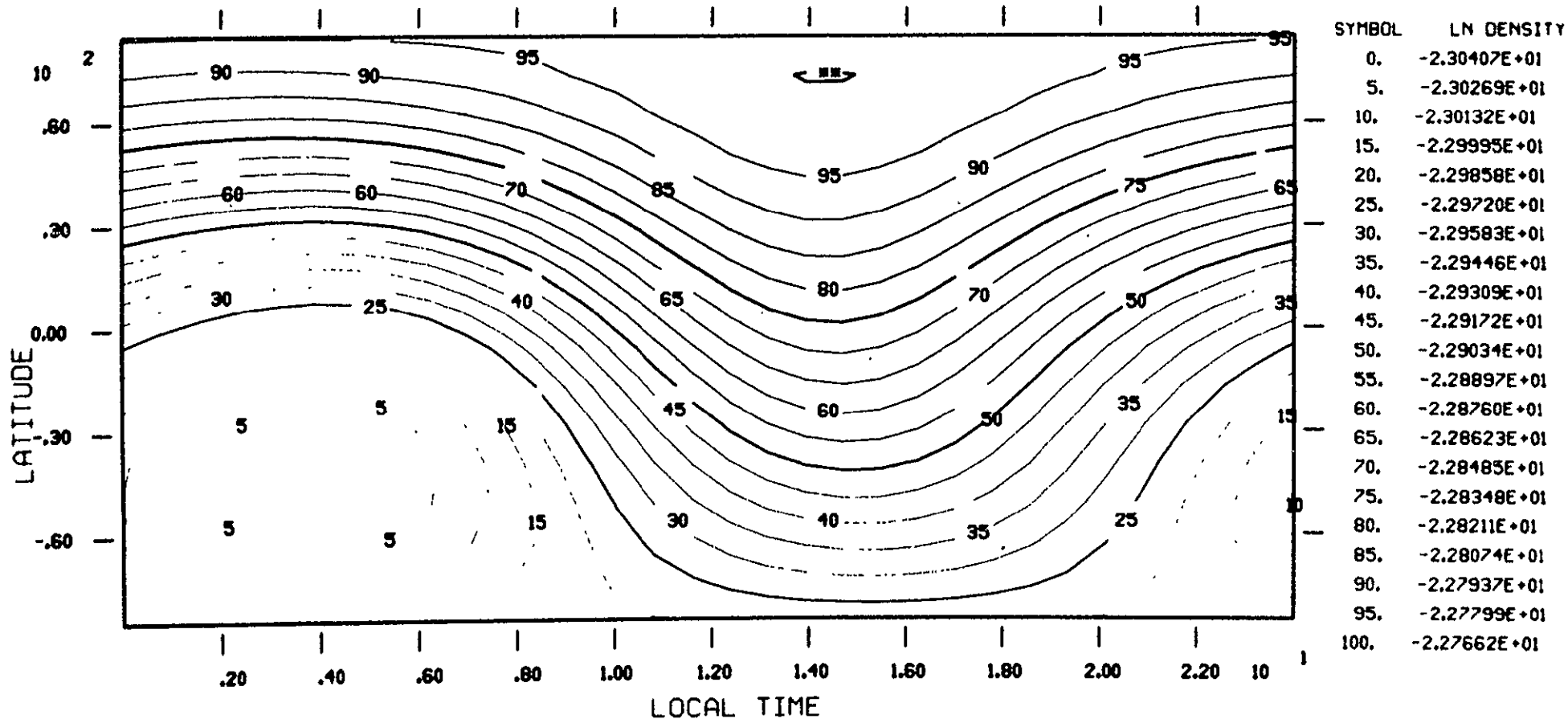
SYMBOL	LN DENSITY
0.	-3.79407E+01
5.	-3.78491E+01
10.	-3.77576E+01
15.	-3.76660E+01
20.	-3.75744E+01
25.	-3.74829E+01
30.	-3.73913E+01
35.	-3.72997E+01
40.	-3.72082E+01
45.	-3.71166E+01
50.	-3.70250E+01
55.	-3.69335E+01
60.	-3.68419E+01
65.	-3.67503E+01
70.	-3.66588E+01
75.	-3.65672E+01
80.	-3.64756E+01
85.	-3.63841E+01
90.	-3.62925E+01
95.	-3.62009E+01
100.	-3.61094E+01

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ATMOSPHERIC DENSITY

MOLECULAR NITROGEN 119.0 KM 10.7 CM FLUX= 92.0 DAY 172.

CONTOUR LEVELS



ATMOSPHERIC DENSITY

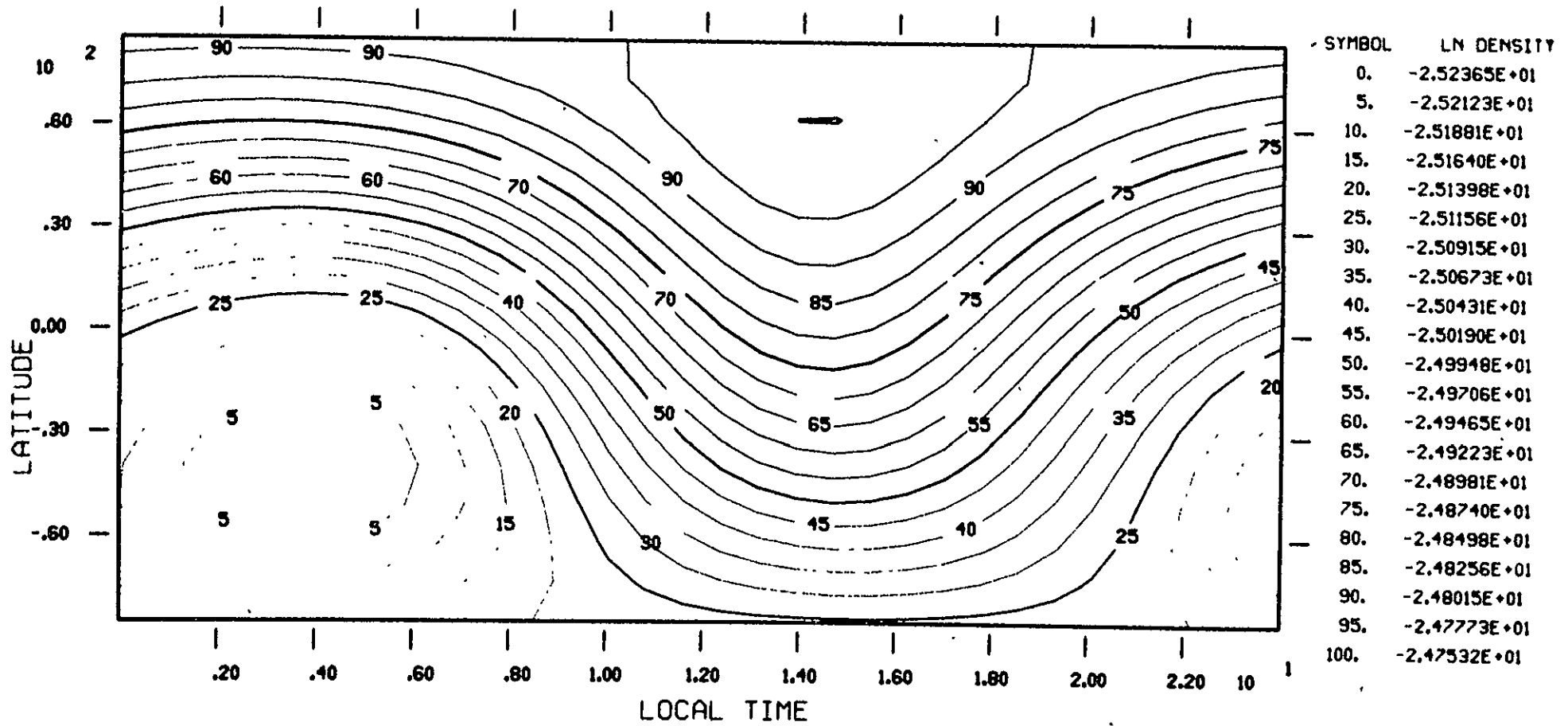
MOLECULAR NITROGEN

143.0 KM

10.7 CM FLUX= 92.0

DAY 172.

CONTOUR LEVELS

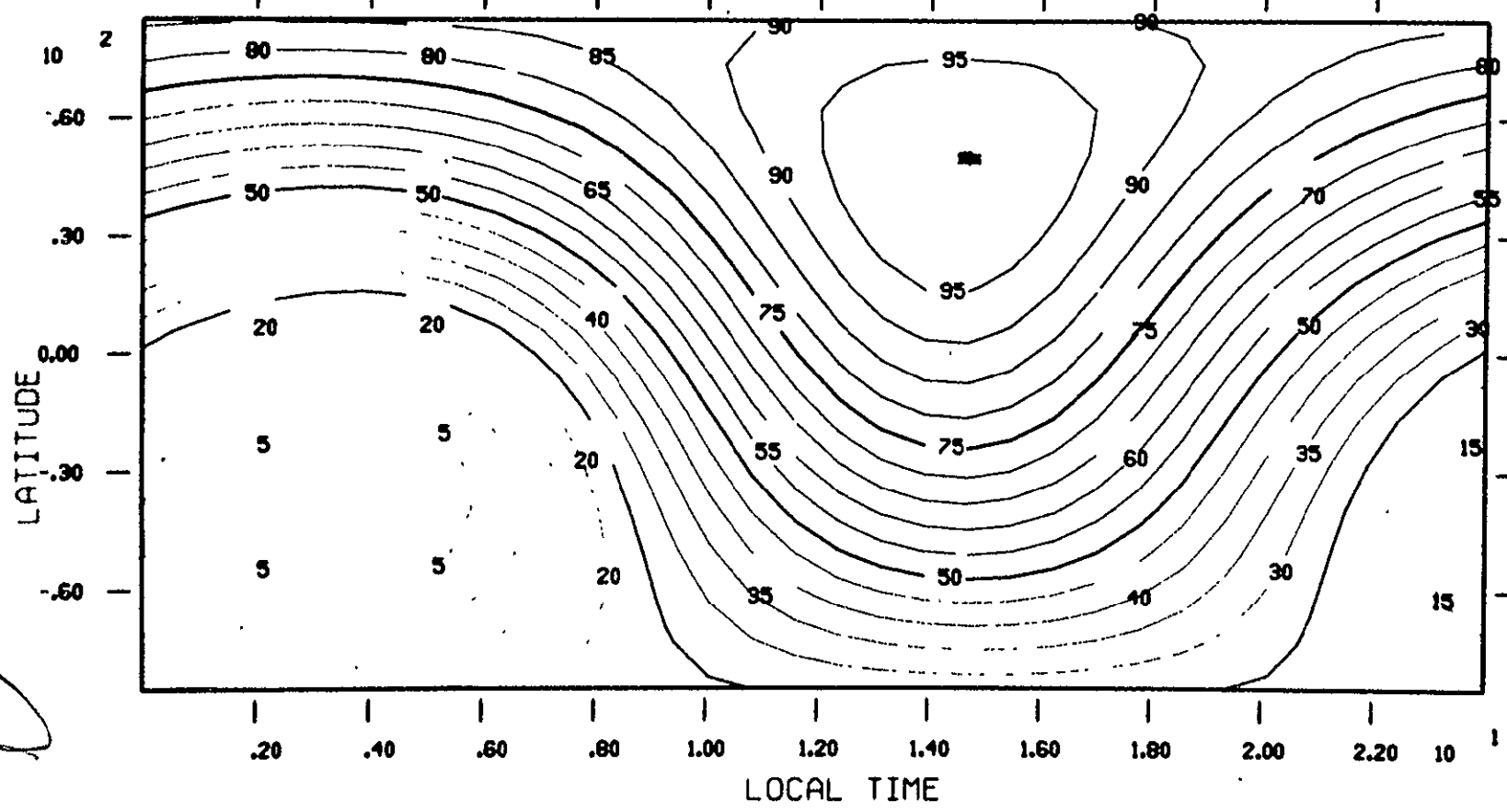


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ATMOSPHERIC DENSITY

MOLECULAR NITROGEN 185.0 KM 10.7 CM FLUX= 92.0 DAY 172.

CONTOUR LEVELS



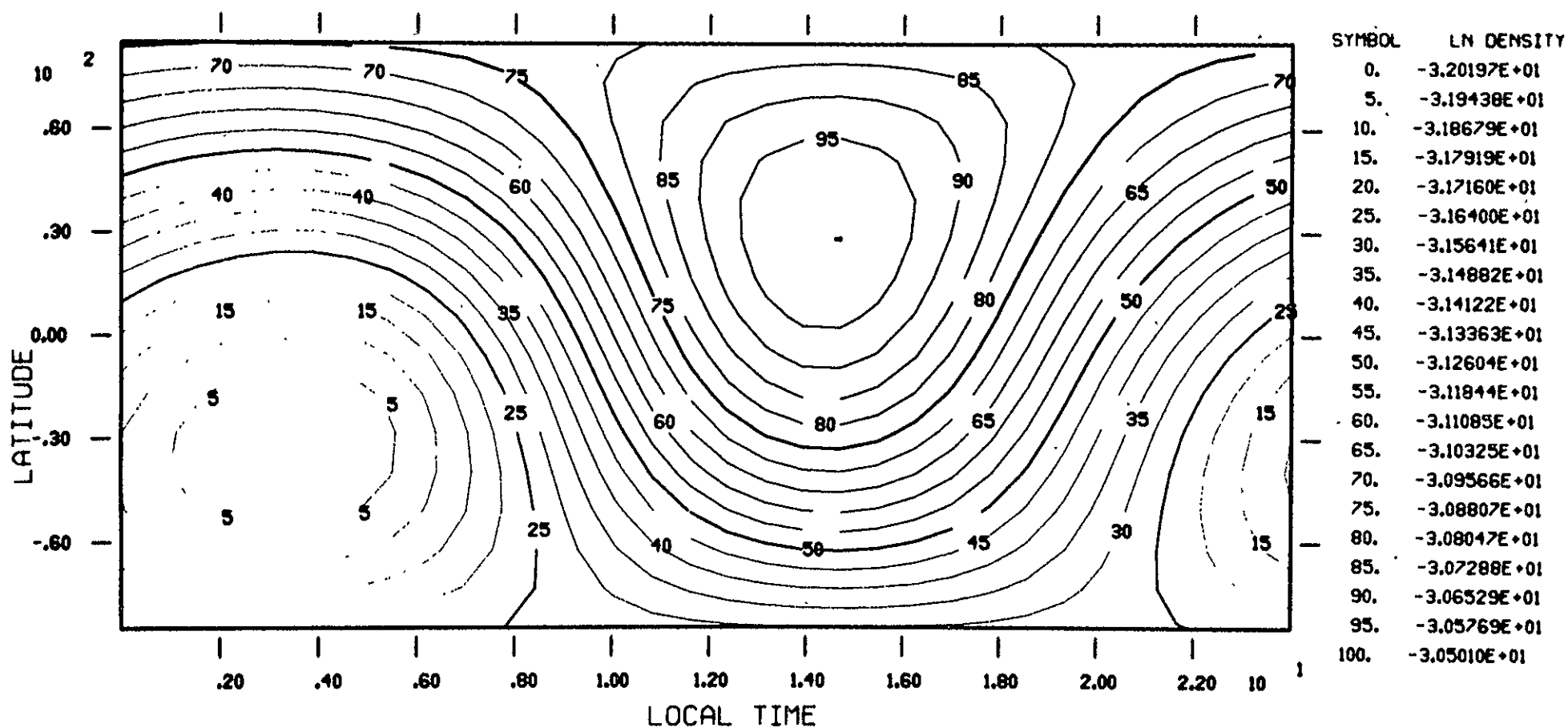
SYMBOL	LN DENSITY
0.	-2.82331E+01
5.	-2.81911E+01
10.	-2.81491E+01
15.	-2.81071E+01
20.	-2.80651E+01
25.	-2.80231E+01
30.	-2.79811E+01
35.	-2.79391E+01
40.	-2.78971E+01
45.	-2.78551E+01
50.	-2.78131E+01
55.	-2.77711E+01
60.	-2.77291E+01
65.	-2.76871E+01
70.	-2.76451E+01
75.	-2.76031E+01
80.	-2.75610E+01
85.	-2.75190E+01
90.	-2.74770E+01
95.	-2.74350E+01
100.	-2.73930E+01

Q-2

ATMOSPHERIC DENSITY

CONTOUR LEVELS

MOLECULAR NITROGEN 260.0 KM 10.7 CM FLUX= 92.0 DAY 172.

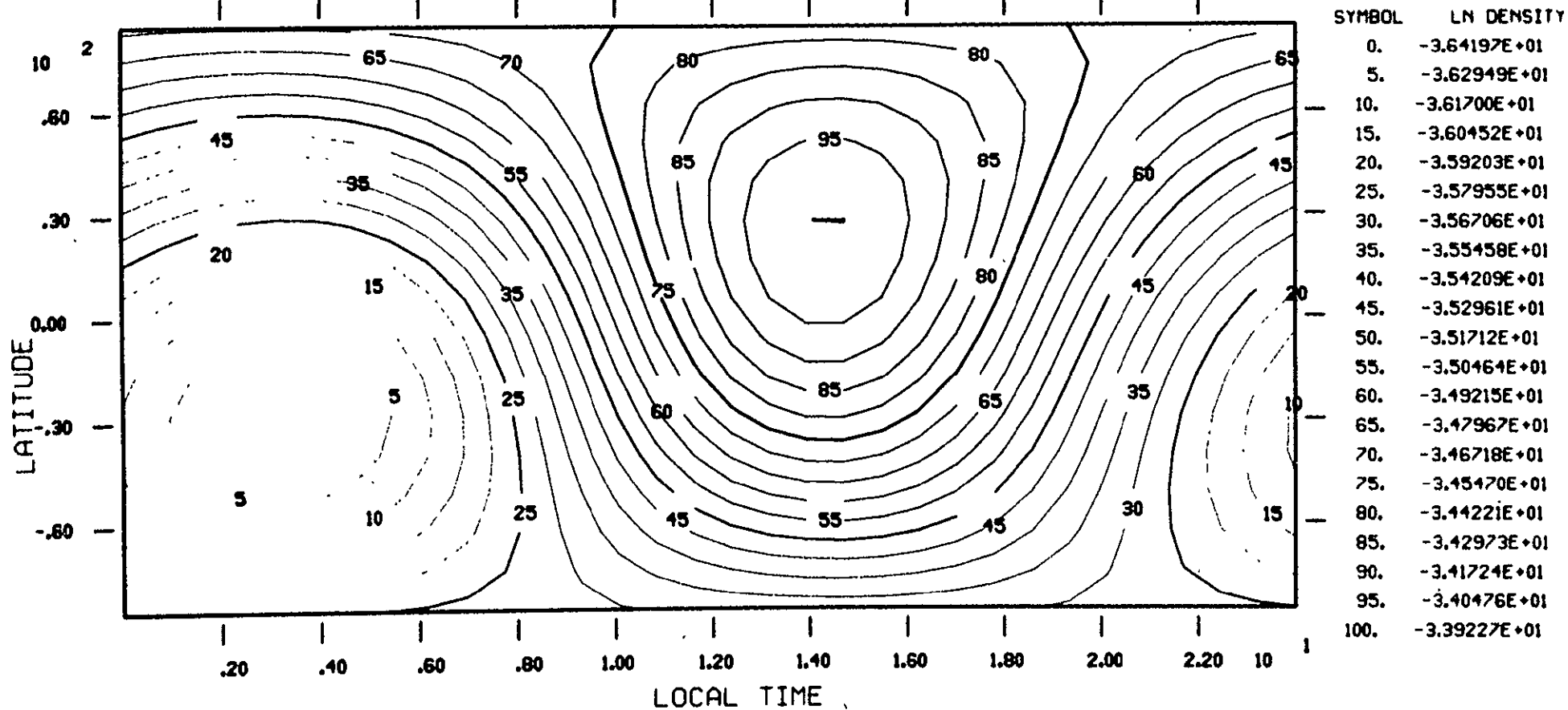


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ATMOSPHERIC DENSITY

CONTOUR LEVELS

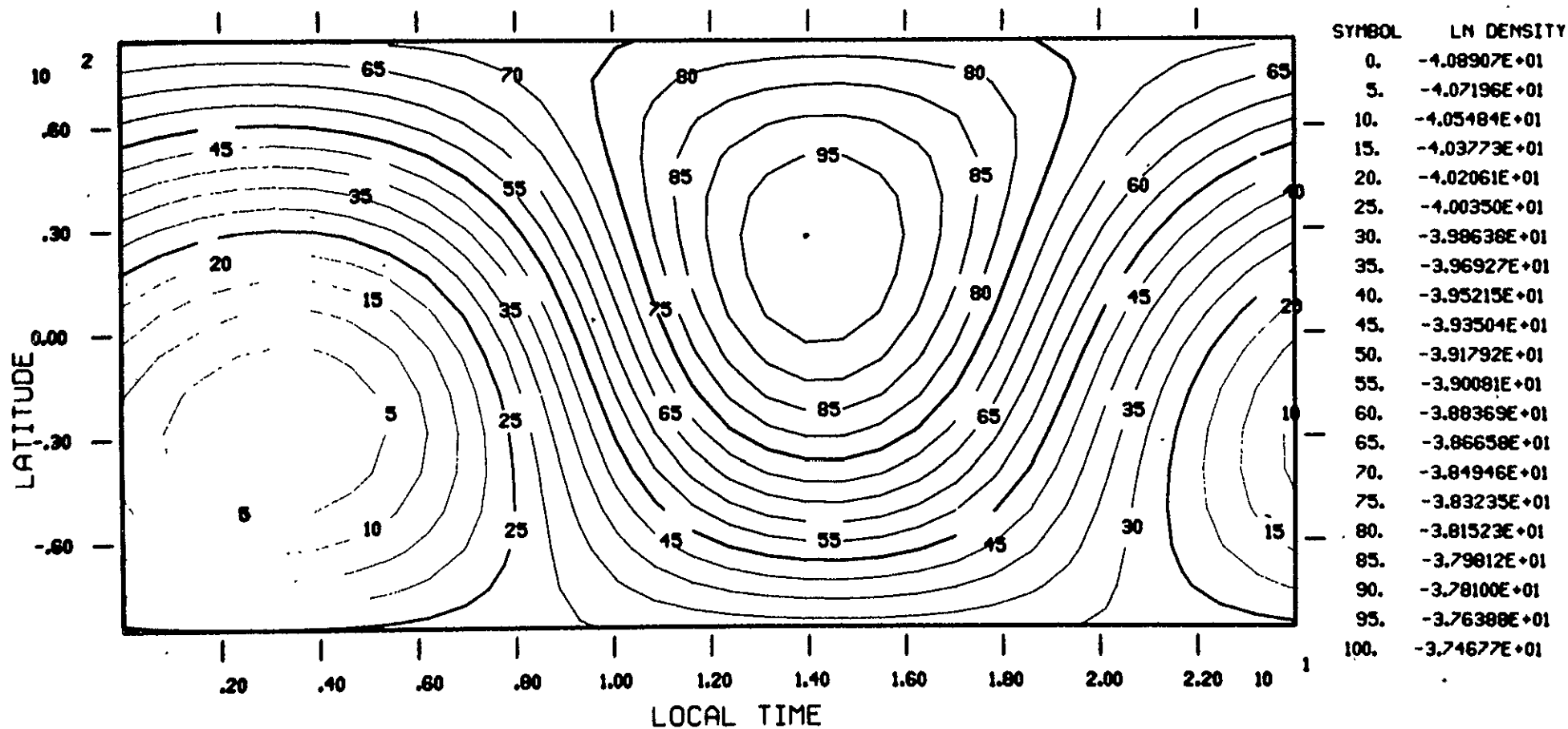
MOLECULAR NITROGEN 365.0 KM 10.7 CM FLUX= 92.0 DAY 172.



ATMOSPHERIC DENSITY

CONTOUR LEVELS

MOLECULAR NITROGEN 470.0 KM 10.7 CM FLUX= 92.0 DAY 172.



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ATMOSPHERIC DENSITY

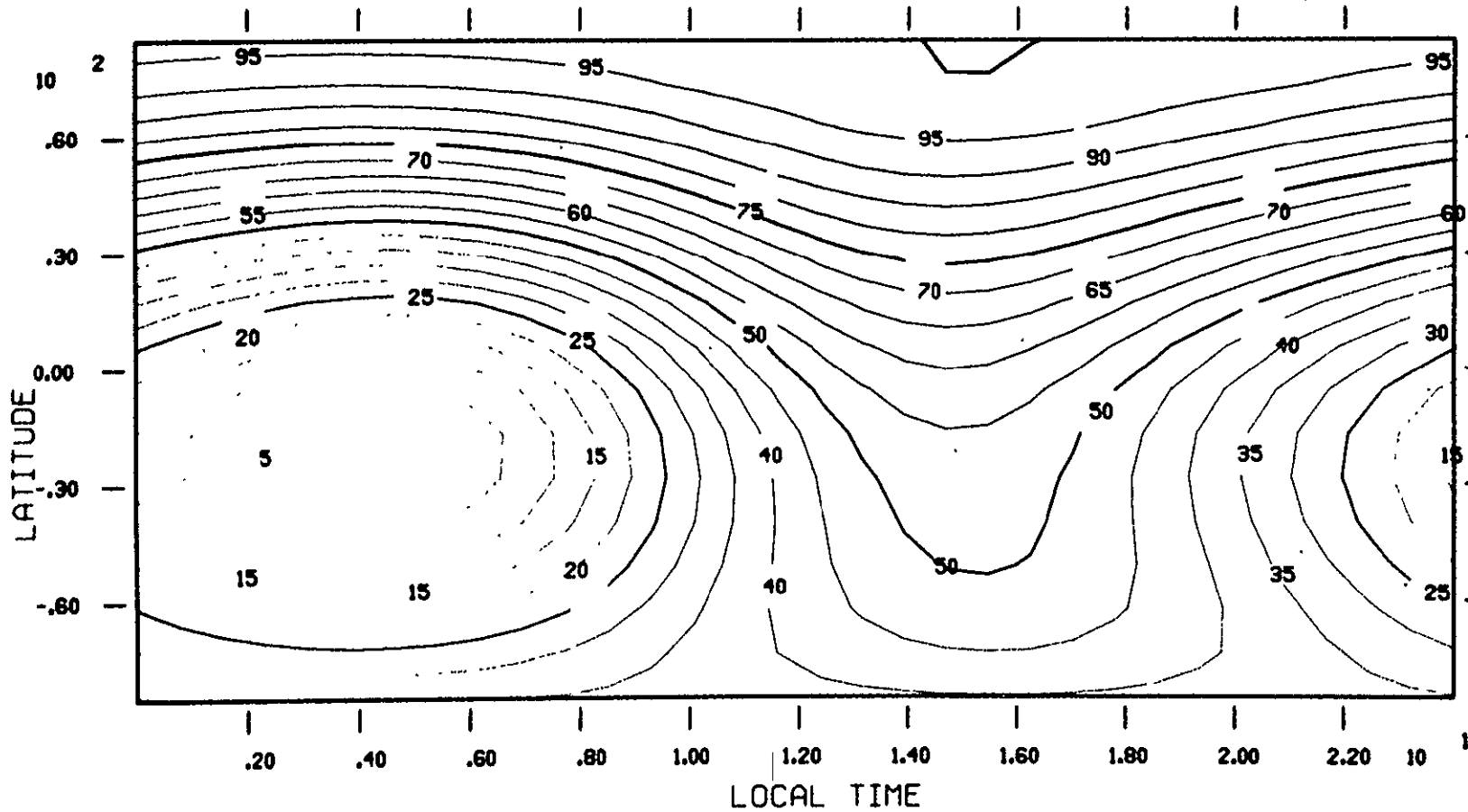
CONTOUR LEVELS

MOLECULAR OXYGEN

119.0 KM

10.7 CM FLUX= 92.0

DAY 172.



SYMBOL	LN DENSITY
0.	-2.45266E+01
5.	-2.45085E+01
10.	-2.44903E+01
15.	-2.44722E+01
20.	-2.44540E+01
25.	-2.44359E+01
30.	-2.44178E+01
35.	-2.43996E+01
40.	-2.43815E+01
45.	-2.43633E+01
50.	-2.43452E+01
55.	-2.43271E+01
60.	-2.43089E+01
65.	-2.42908E+01
70.	-2.42726E+01
75.	-2.42545E+01
80.	-2.42364E+01
85.	-2.42182E+01
90.	-2.42001E+01
95.	-2.41820E+01
100.	-2.41638E+01

ATMOSPHERIC DENSITY

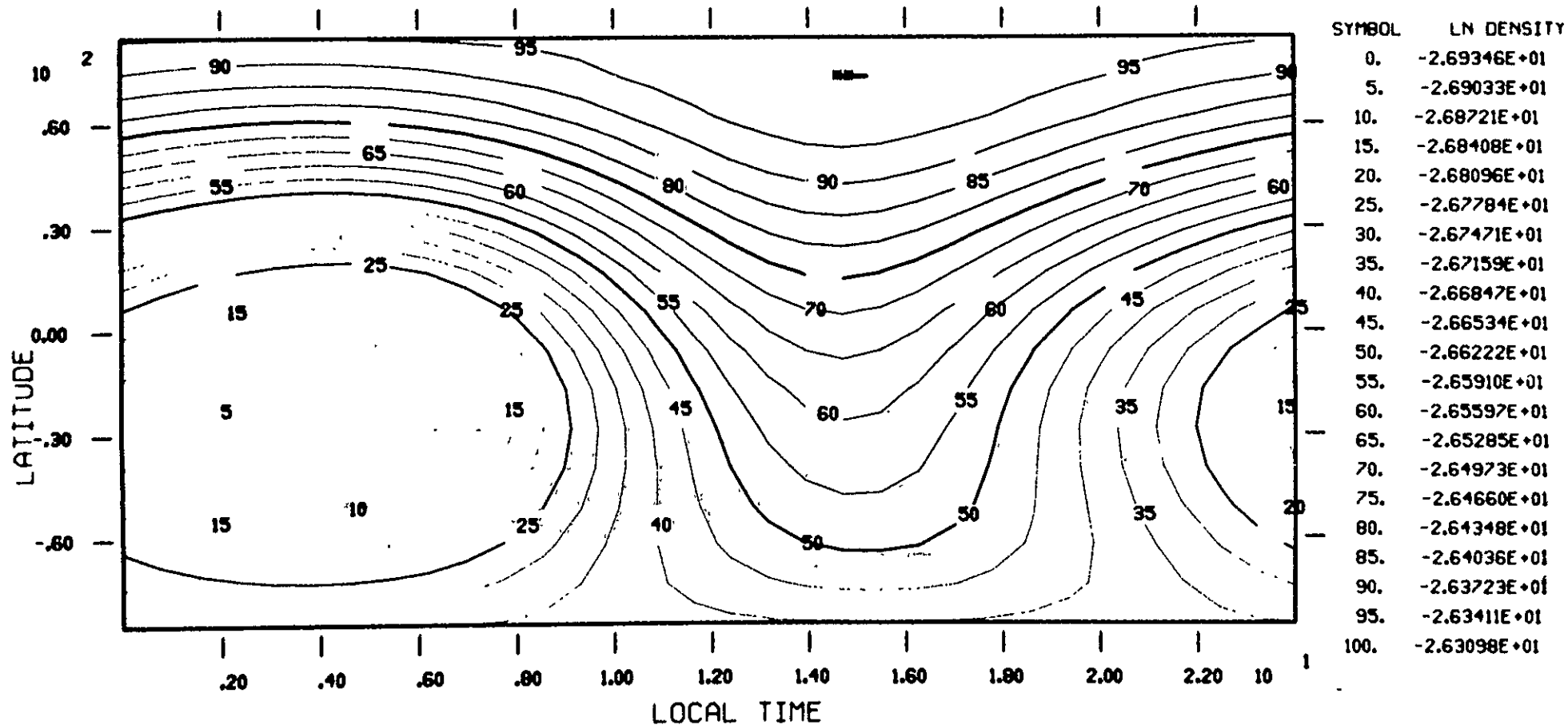
CONTOUR LEVELS

MOLECULAR OXYGEN

143.0 KM

10.7 CM FLUX= 92.0

DAY 172.



ATMOSPHERIC DENSITY

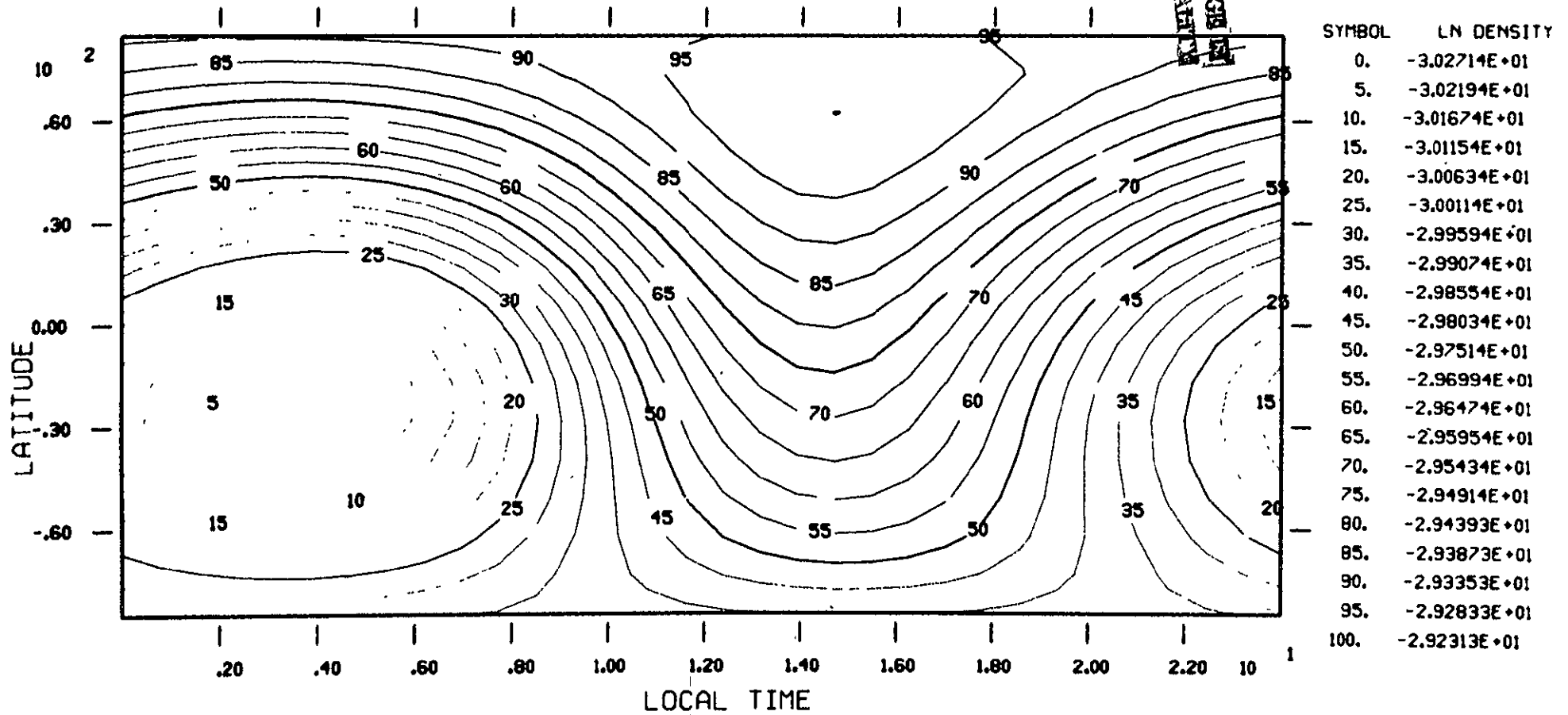
MOLECULAR OXYGEN

185.0 KM

10.7 CM FLUX= 92.0

DAY 172.

CONTOUR LEVELS



ATMOSPHERIC DENSITY

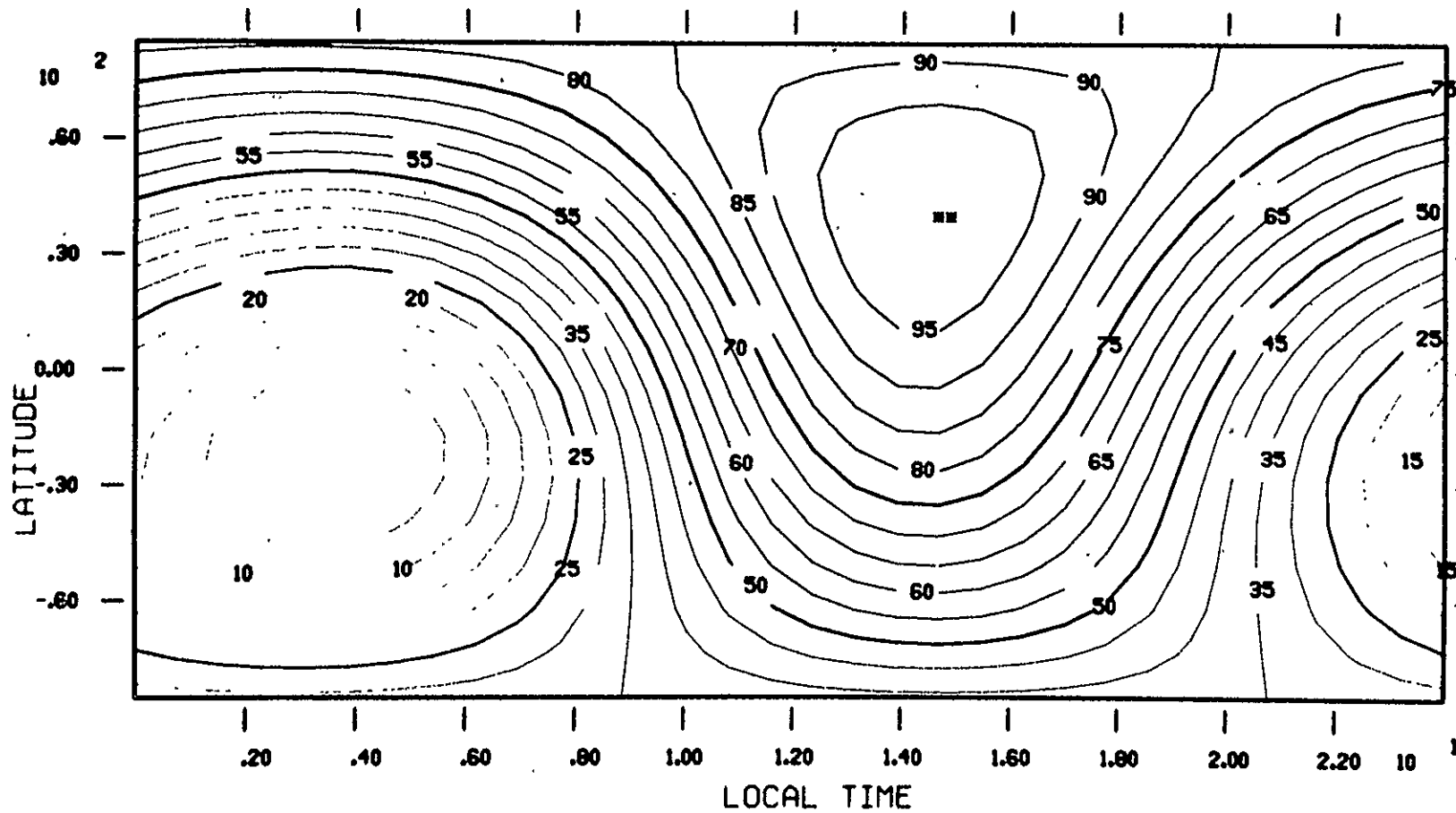
CONTOUR LEVELS

MOLECULAR OXYGEN

260.0 KM

10.7 CM FLUX= 92.0

DAY 172.



SYMBOL	LN DENSITY
0.	-3.45854E+01
5.	-3.44961E+01
10.	-3.44067E+01
15.	-3.43173E+01
20.	-3.42279E+01
25.	-3.41385E+01
30.	-3.40491E+01
35.	-3.39597E+01
40.	-3.38703E+01
45.	-3.37810E+01
50.	-3.36916E+01
55.	-3.36022E+01
60.	-3.35128E+01
65.	-3.34234E+01
70.	-3.33340E+01
75.	-3.32446E+01
80.	-3.31553E+01
85.	-3.30659E+01
90.	-3.29765E+01
95.	-3.28871E+01
100.	-3.27977E+01

Fig
14d

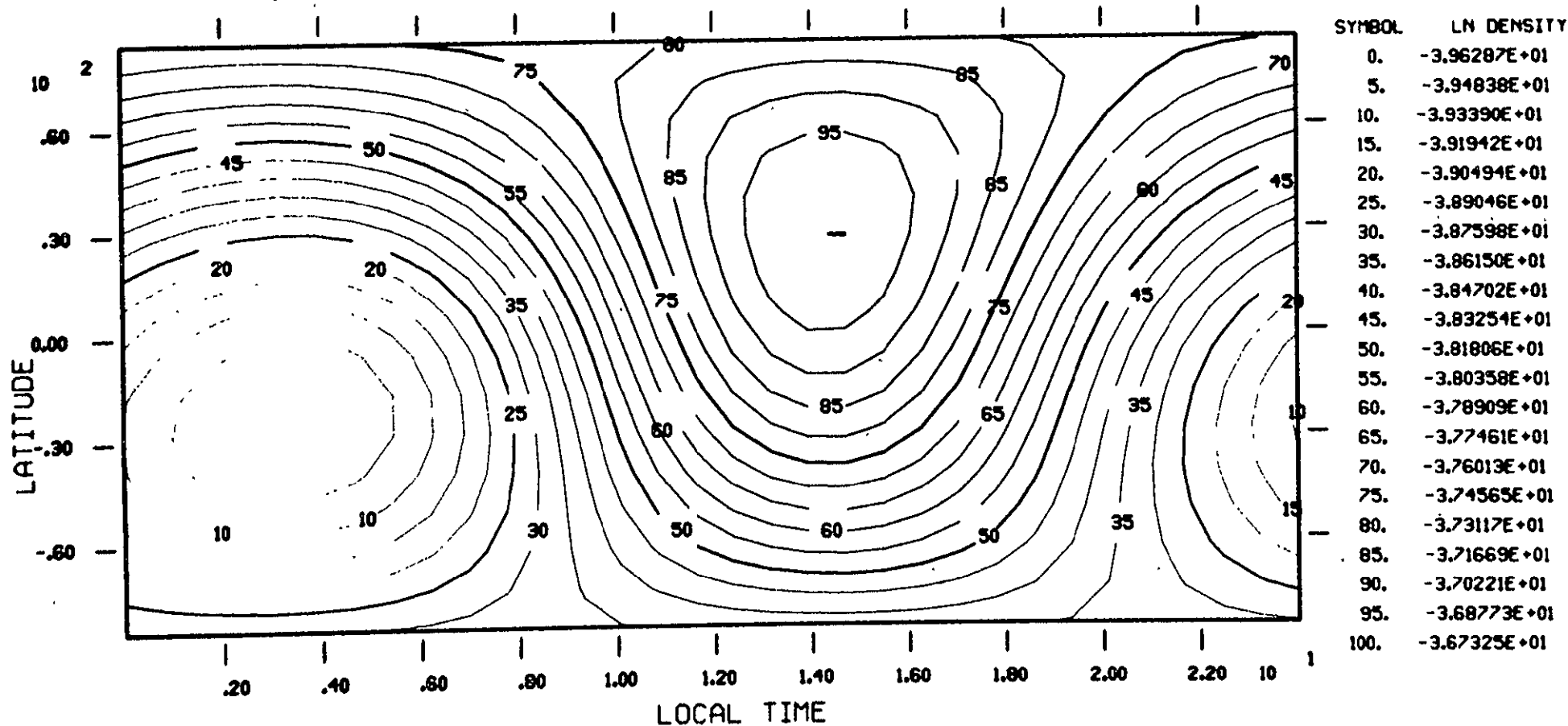
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ATMOSPHERIC DENSITY

CONTOUR LEVELS

MOLECULAR OXYGEN 365.0 KM 10.7 CM FLUX= 92.0 DAY 172.



ATMOSPHERIC DENSITY

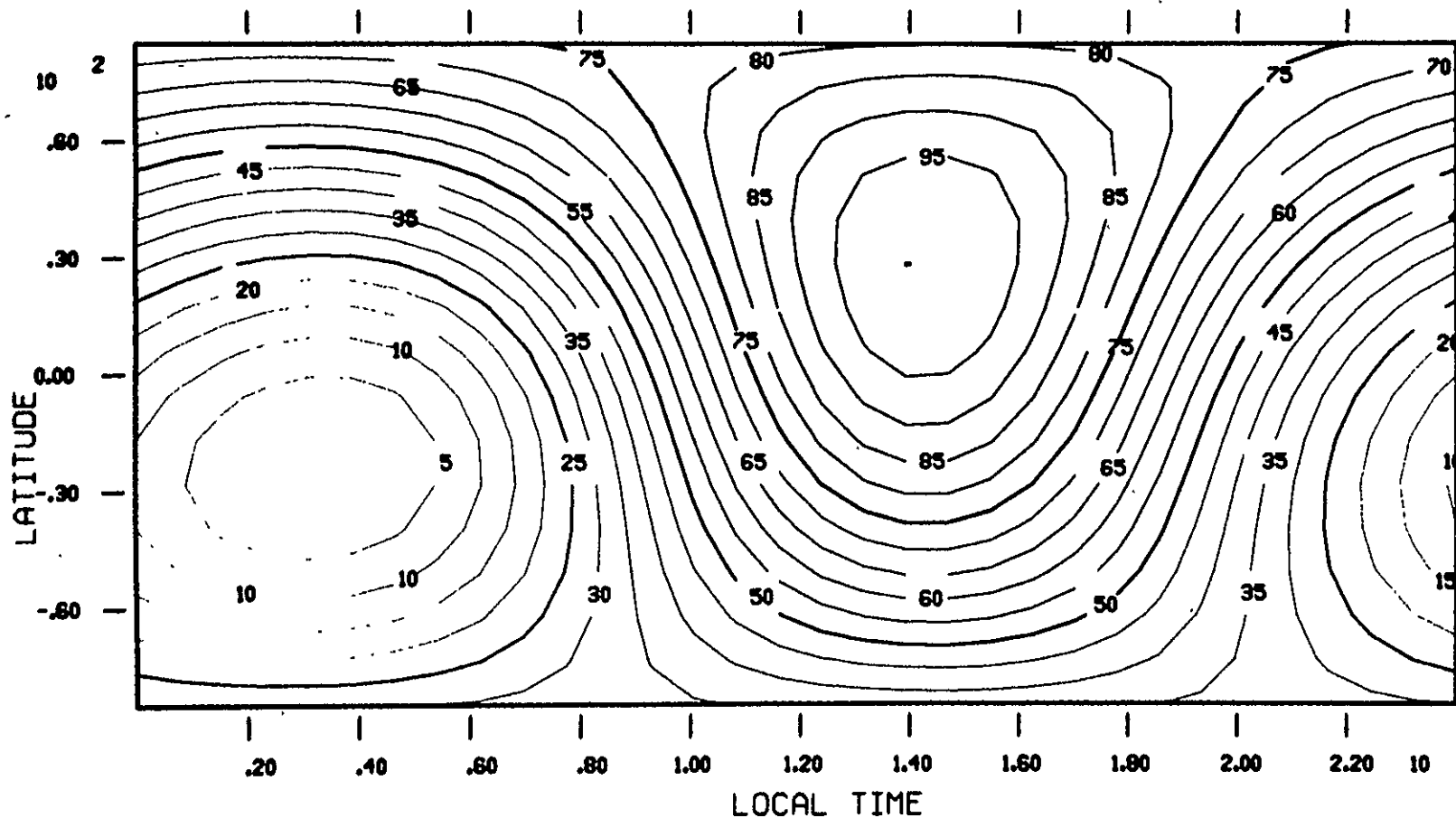
CONTOUR LEVELS

MOLECULAR OXYGEN

470.0 KM

10.7 CM FLUX= 92.0

DAY 172.



SYMBOL	LN DENSITY
0.	-4.47033E+01
5.	-4.45060E+01
10.	-4.43087E+01
15.	-4.41114E+01
20.	-4.39141E+01
25.	-4.37168E+01
30.	-4.35195E+01
35.	-4.33222E+01
40.	-4.31249E+01
45.	-4.29276E+01
50.	-4.27304E+01
55.	-4.25331E+01
60.	-4.23358E+01
65.	-4.21385E+01
70.	-4.19412E+01
75.	-4.17439E+01
80.	-4.15466E+01
85.	-4.13493E+01
90.	-4.11520E+01
95.	-4.09547E+01
100.	-4.07574E+01

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ATMOSPHERIC DENSITY

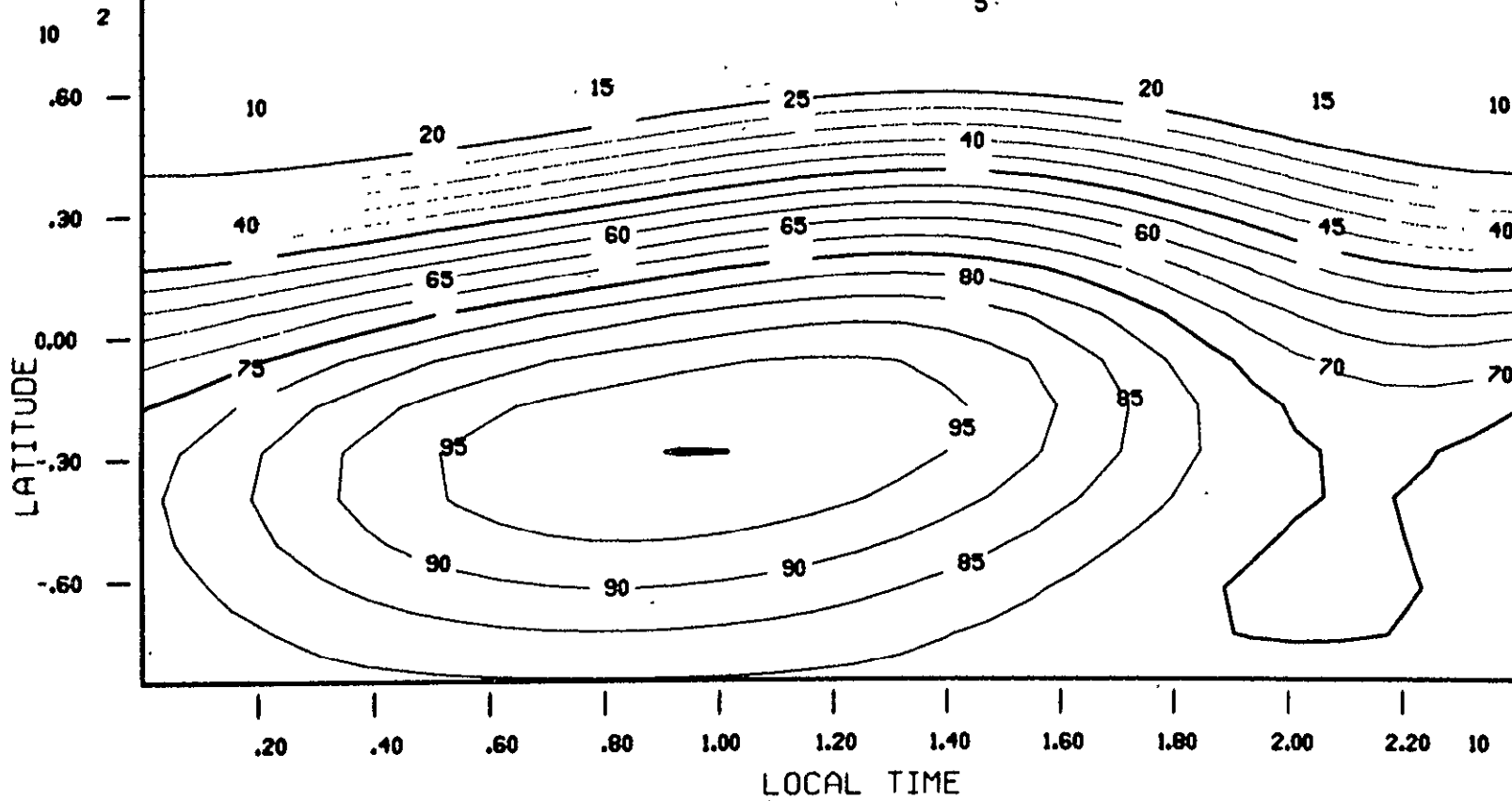
CONTOUR LEVELS

ATOMIC OXYGEN

119.0 KM

10.7 CM FLUX= 92.0

DAY 172.



SYMBOL	LN DENSITY
0.	-2.73503E+01
5.	-2.73329E+01
10.	-2.73155E+01
15.	-2.72981E+01
20.	-2.72807E+01
25.	-2.72632E+01
30.	-2.72458E+01
35.	-2.72284E+01
40.	-2.72110E+01
45.	-2.71936E+01
50.	-2.71762E+01
55.	-2.71588E+01
60.	-2.71413E+01
65.	-2.71239E+01
70.	-2.71065E+01
75.	-2.70891E+01
80.	-2.70717E+01
85.	-2.70543E+01
90.	-2.70368E+01
95.	-2.70194E+01
100.	-2.70020E+01

ATMOSPHERIC DENSITY

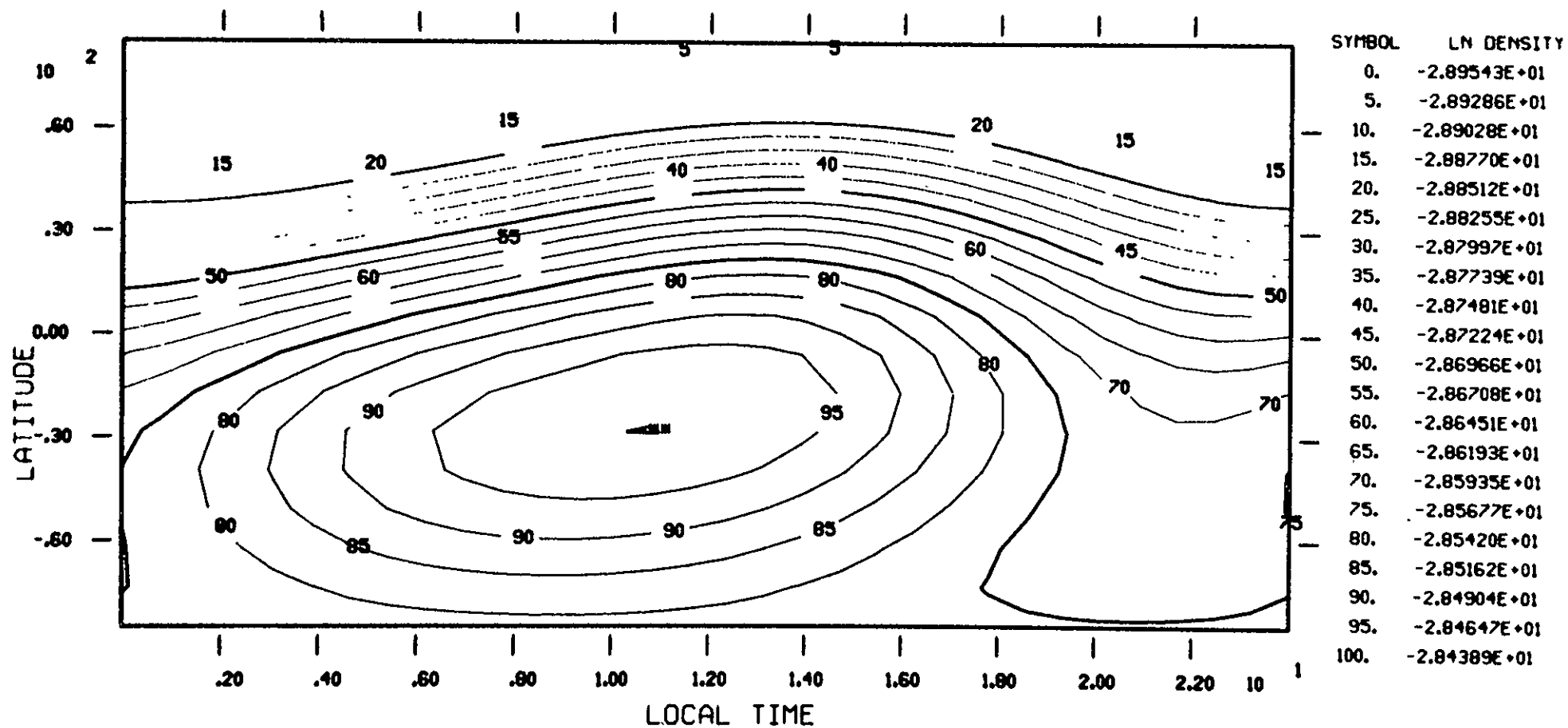
CONTOUR LEVELS

ATOMIC OXYGEN

143.0 KM

10.7 CM FLUX* 92.0

DAY 172.



ATMOSPHERIC DENSITY

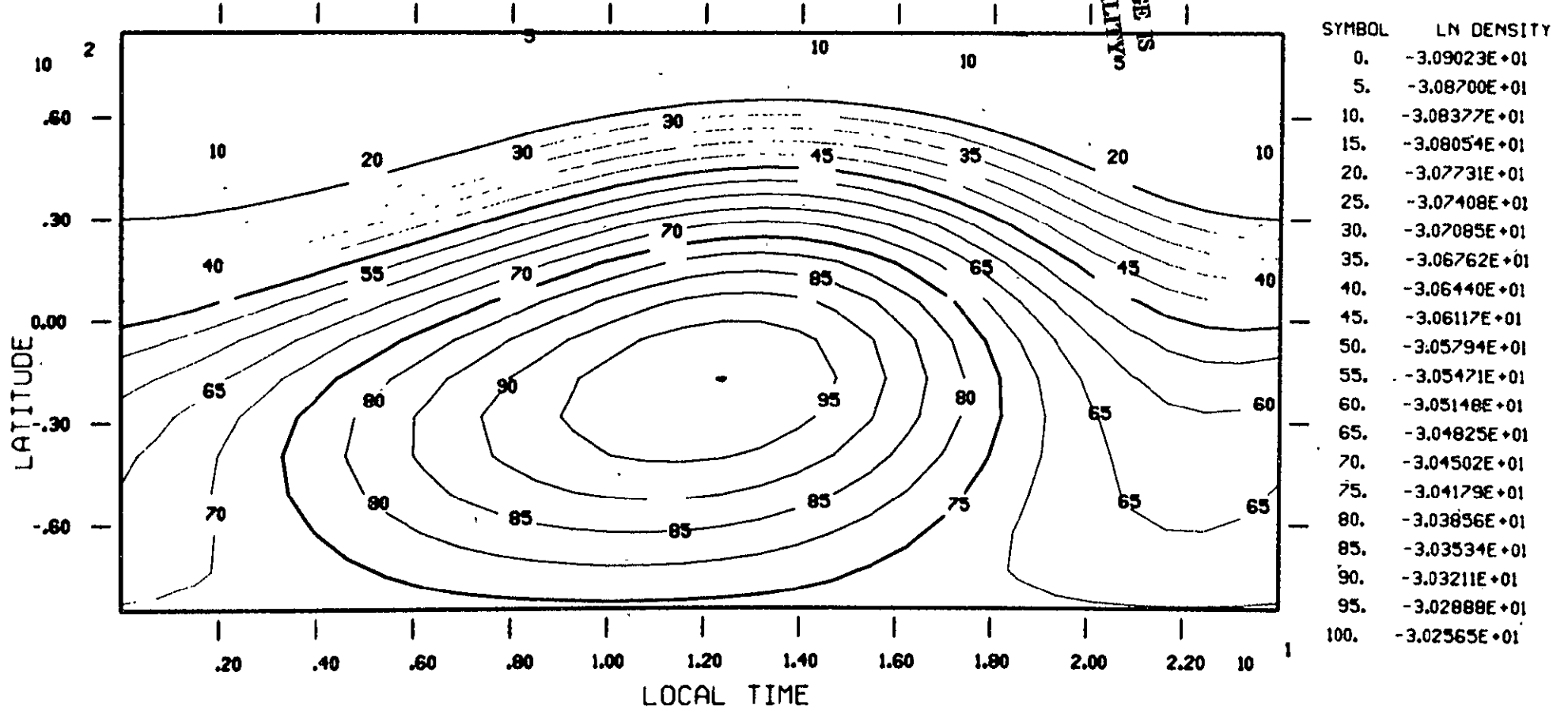
ATOMIC OXYGEN

185.0 KM

10.7 CM FLUX= 92.0

DAY 172.

CONTOUR LEVELS



ATMOSPHERIC DENSITY

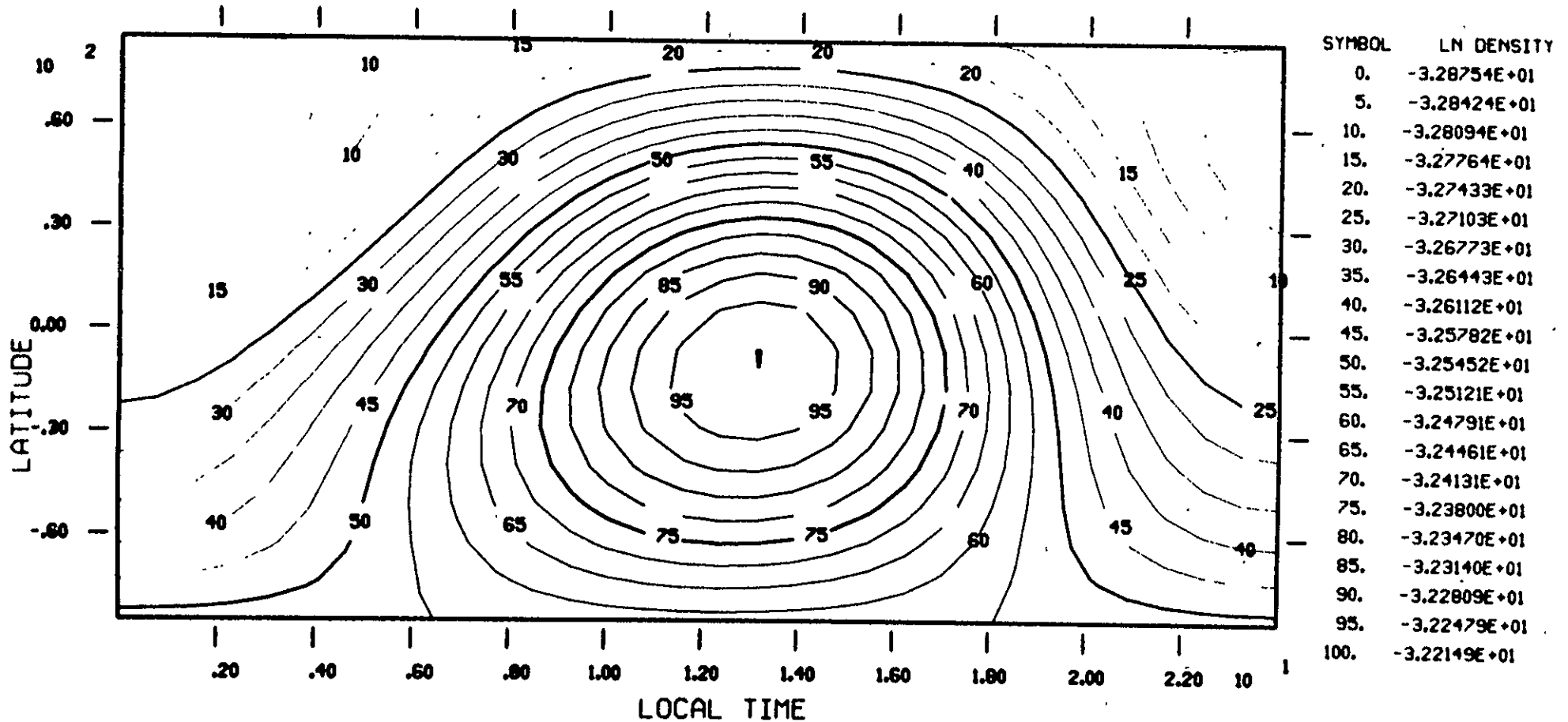
ATOMIC OXYGEN

260.0 KM

10.7 CM FLUX= 92.0

DAY 172.

CONTOUR LEVELS



ATMOSPHERIC DENSITY

ATOMIC OXYGEN

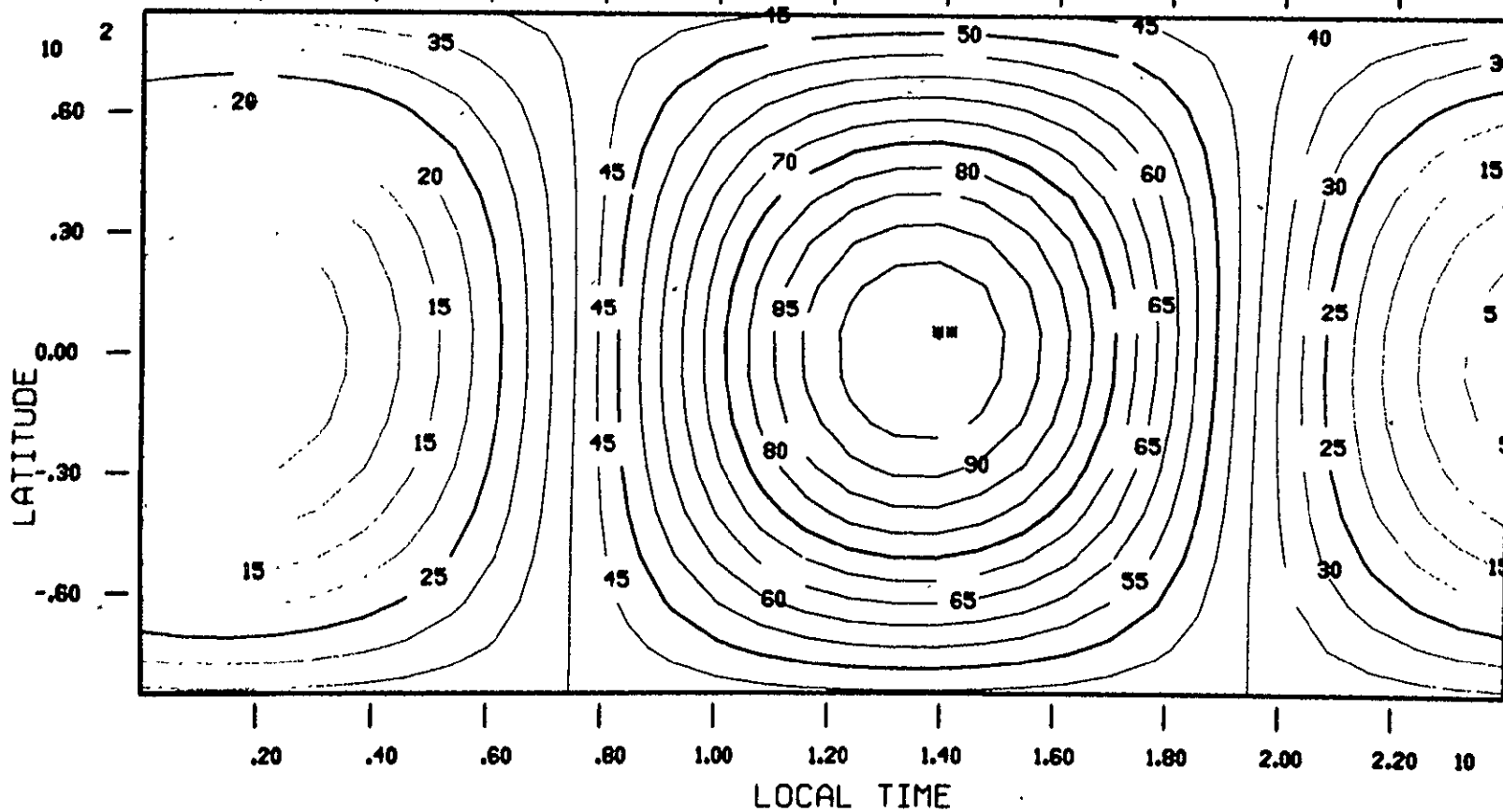
365.0 KM

10.7 CM FLUX= 92.0

DAY 172.

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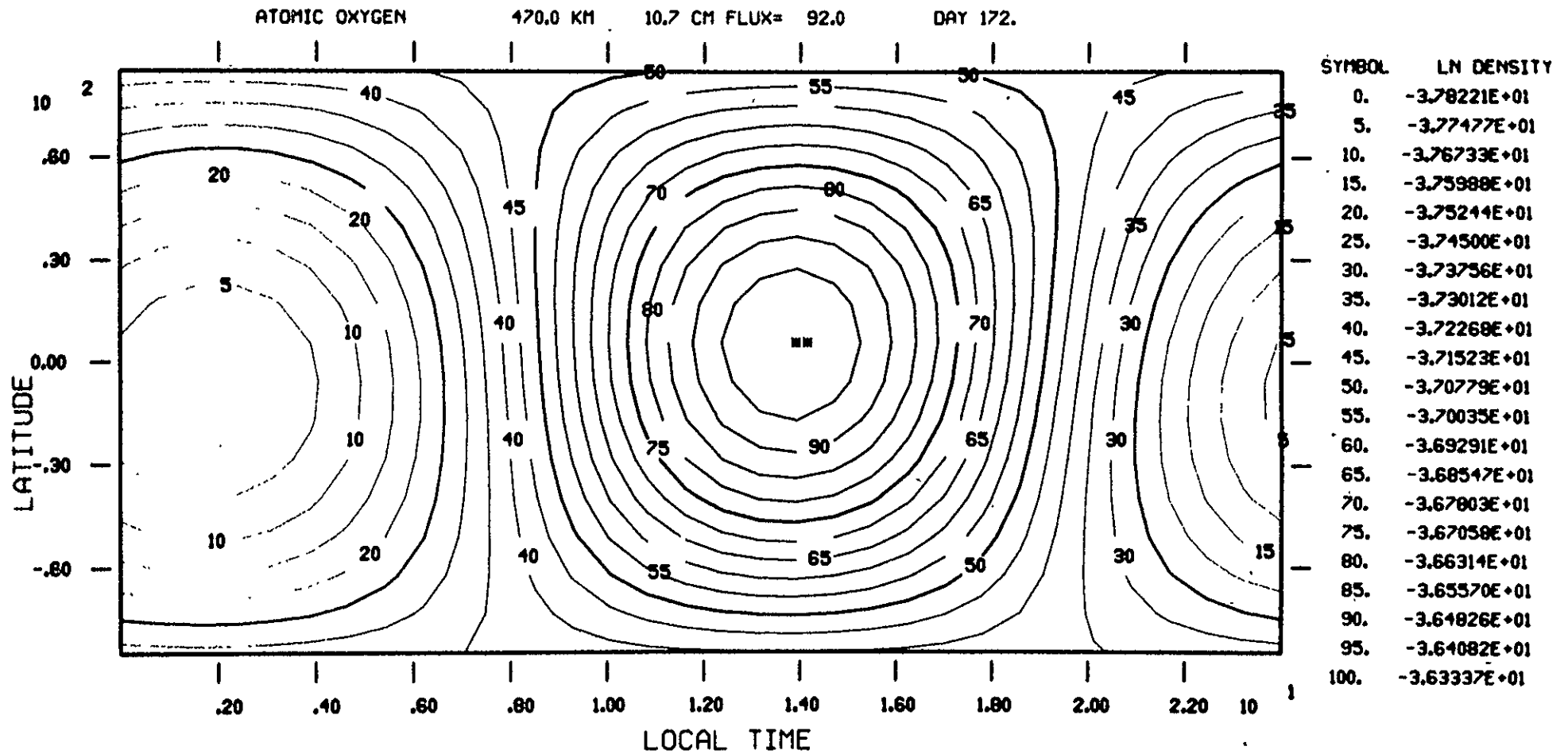
CONTOUR LEVELS



SYMBOL	LN DENSITY
0.	-3.51941E+01
5.	-3.51453E+01
10.	-3.50965E+01
15.	-3.50477E+01
20.	-3.49989E+01
25.	-3.49501E+01
30.	-3.49012E+01
35.	-3.48524E+01
40.	-3.48036E+01
45.	-3.47548E+01
50.	-3.47060E+01
55.	-3.46572E+01
60.	-3.46083E+01
65.	-3.45595E+01
70.	-3.45107E+01
75.	-3.44619E+01
80.	-3.44131E+01
85.	-3.43643E+01
90.	-3.43155E+01
95.	-3.42666E+01
100.	-3.42178E+01

ATMOSPHERIC DENSITY

CONTOUR LEVELS



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ATMOSPHERIC DENSITY

MOLECULAR NITROGEN

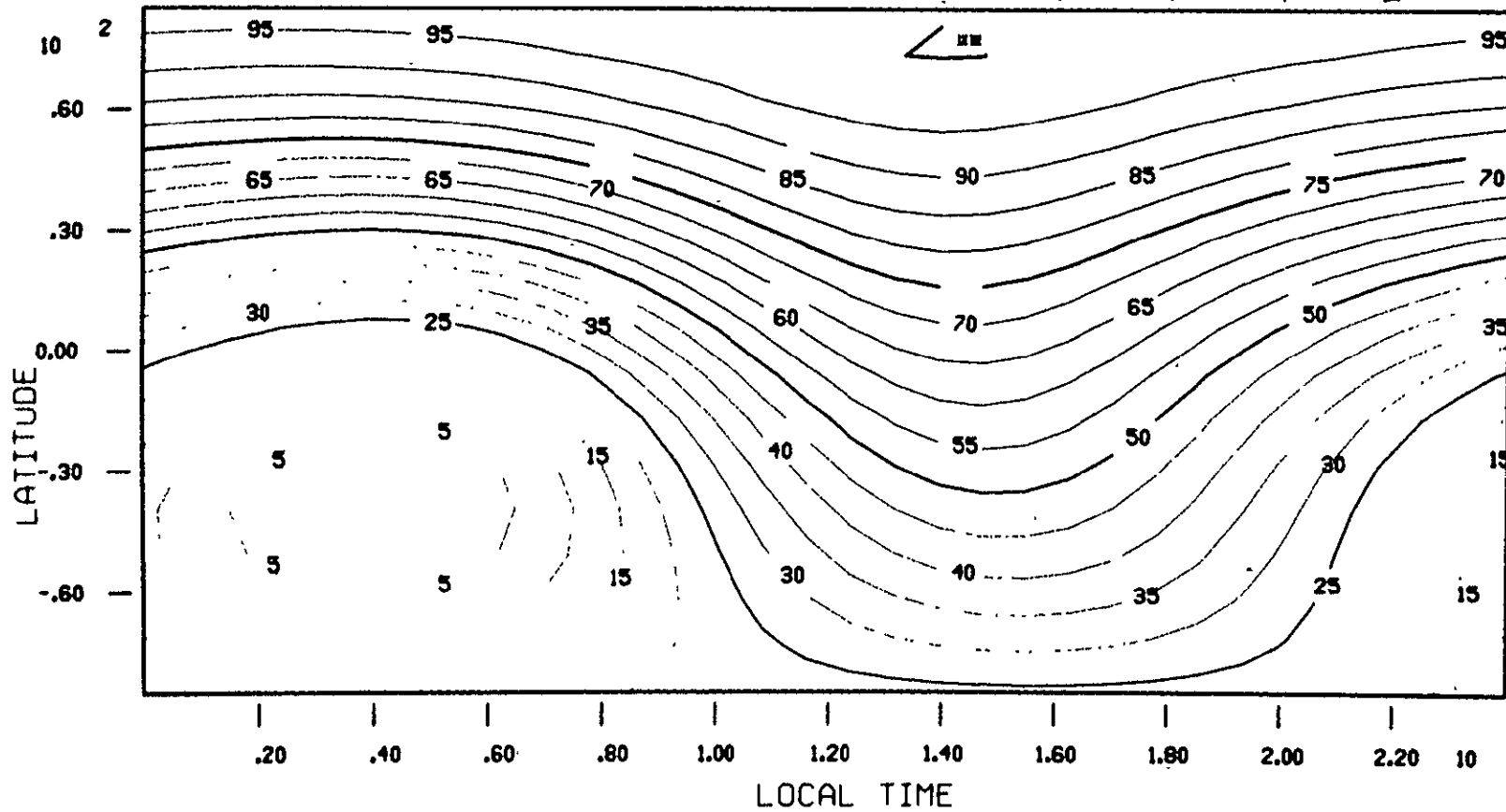
119.0 KI

10.7 CM FLUX= 140.0

DAY 172.

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CONTOUR LEVELS



SYMBOL	LN DENSITY
0.	-2.29098E+01
5.	-2.28971E+01
10.	-2.28844E+01
15.	-2.28717E+01
20.	-2.28590E+01
25.	-2.28463E+01
30.	-2.28336E+01
35.	-2.28209E+01
40.	-2.28082E+01
45.	-2.27955E+01
50.	-2.27828E+01
55.	-2.27701E+01
60.	-2.27574E+01
65.	-2.27447E+01
70.	-2.27320E+01
75.	-2.27193E+01
80.	-2.27066E+01
85.	-2.26939E+01
90.	-2.26812E+01
95.	-2.26685E+01
100.	-2.26558E+01

ATMOSPHERIC DENSITY

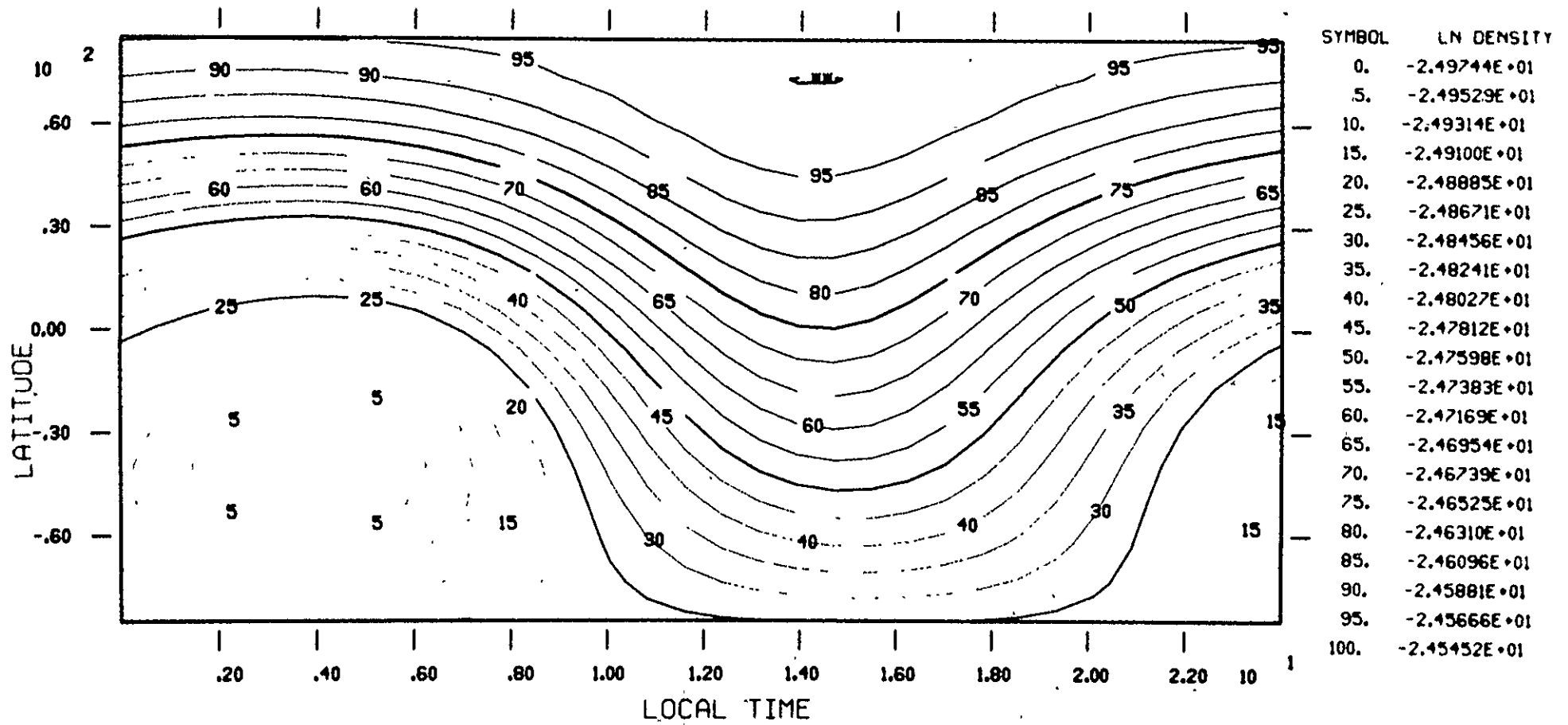
MOLECULAR NITROGEN

143.0 KM

10.7 CM FLUX= 140.0

DAY 172.

CONTOUR LEVELS



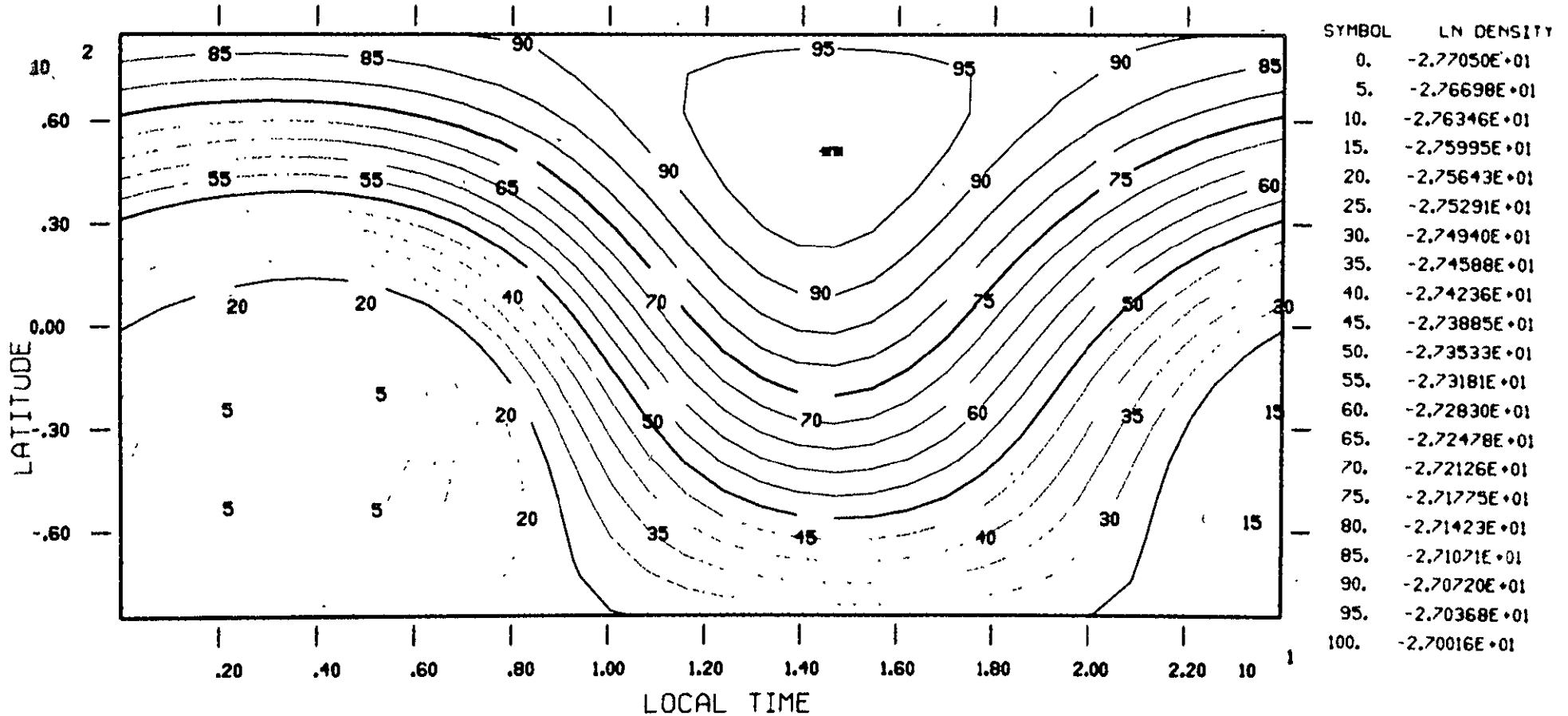
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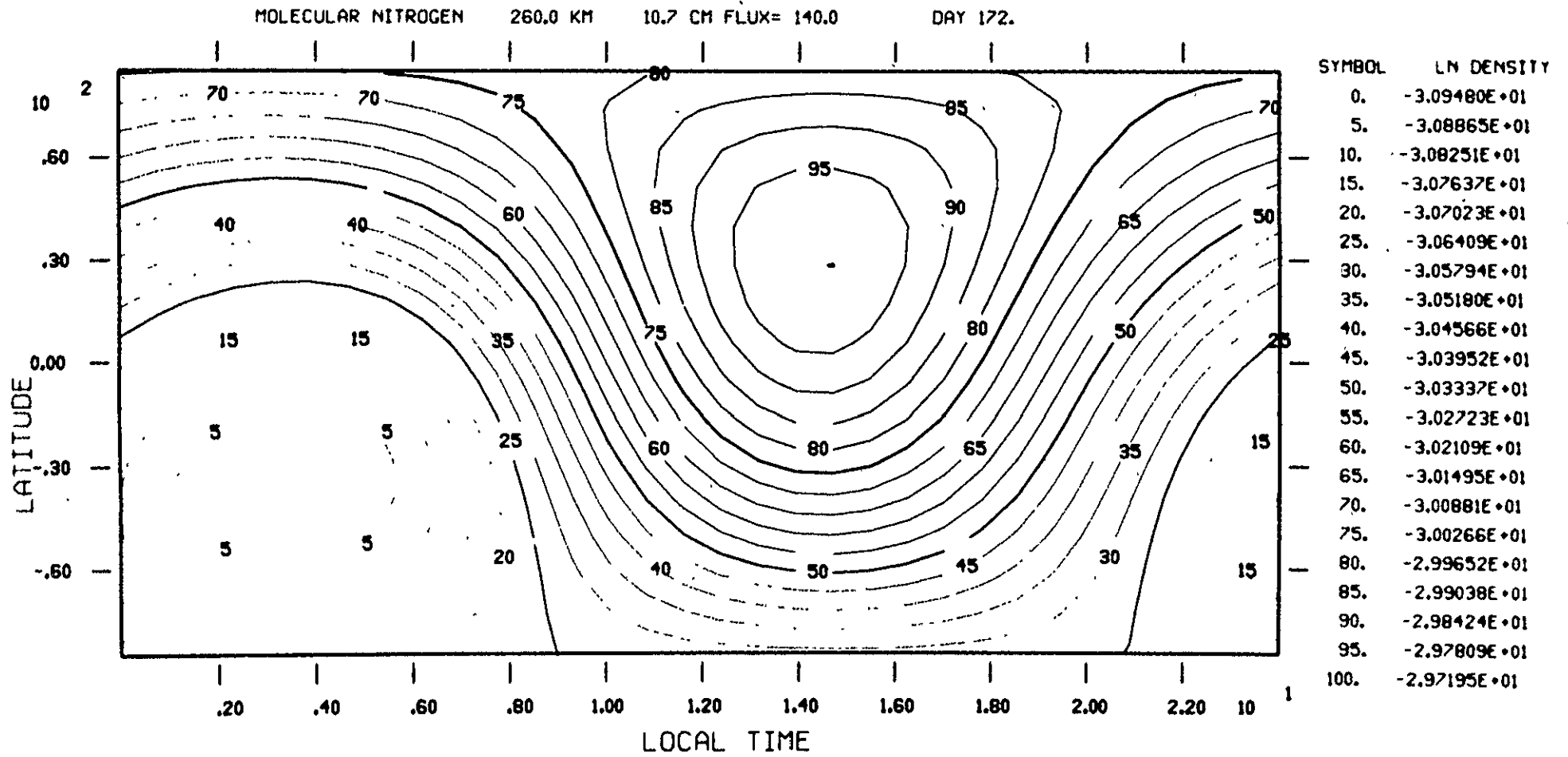
CONTOUR LEVELS

MOLECULAR NITROGEN 185.0 KM 10.7 CM FLUX= 140.0 DAY 172.



ATMOSPHERIC DENSITY

CONTOUR LEVELS

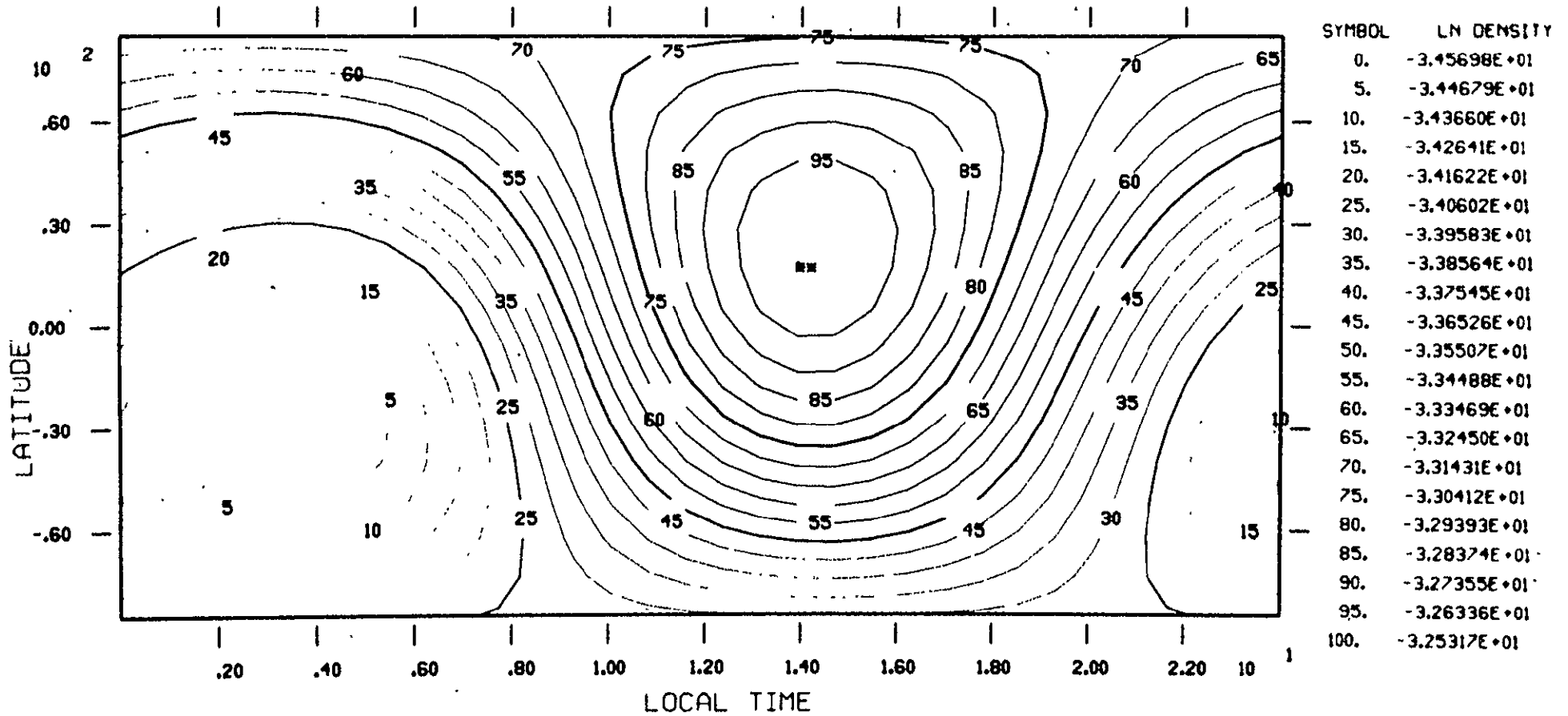


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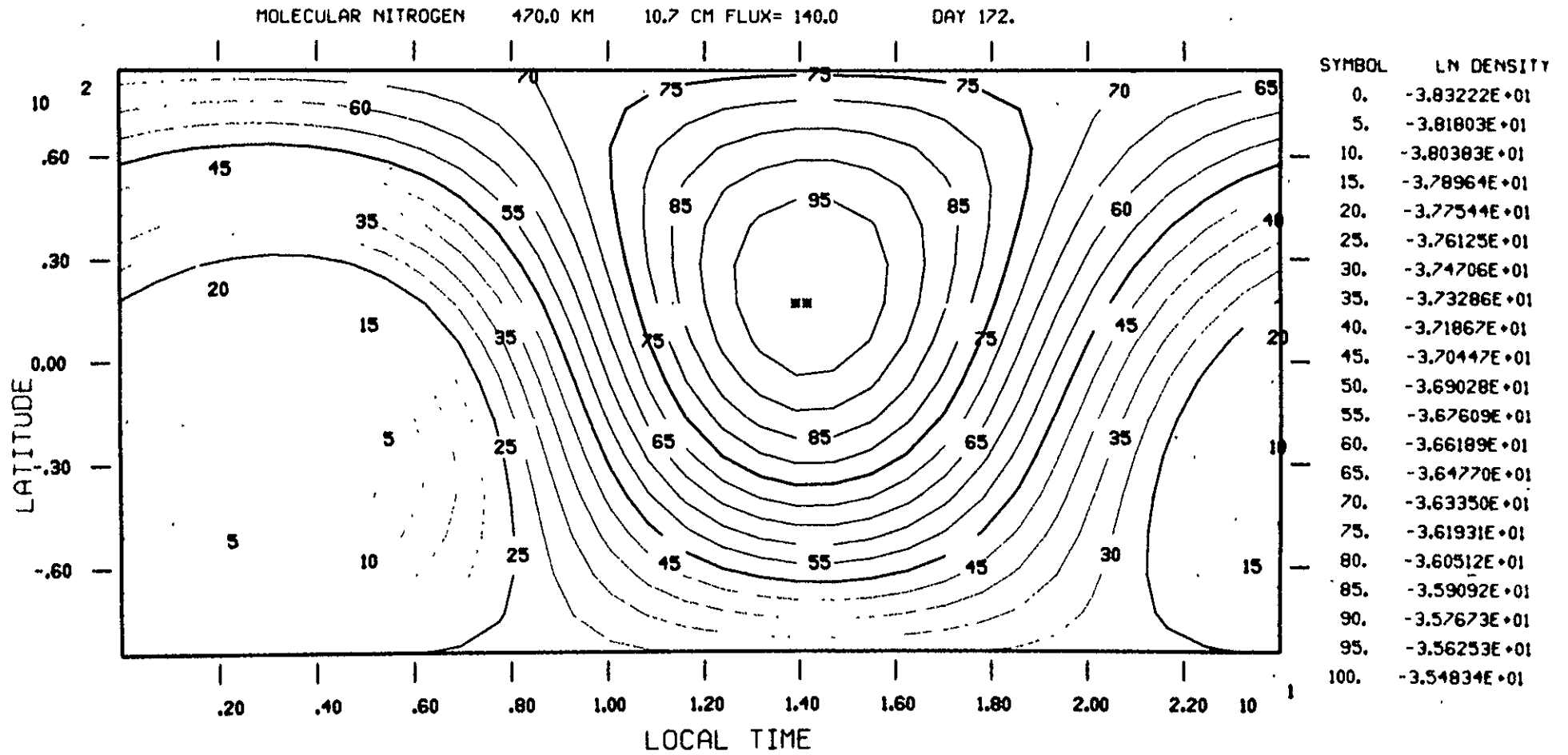
MOLECULAR NITROGEN 365.0 KM 10.7 CM FLUX= 140.0 DAY 172.

CONTOUR LEVELS



ATMOSPHERIC DENSITY

CONTOUR LEVELS



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ATMOSPHERIC DENSITY

MOLECULAR OXYGEN 119.0 KM 10.7 CM FLUX= 140.0 DAY 172.

CONTOUR LEVELS

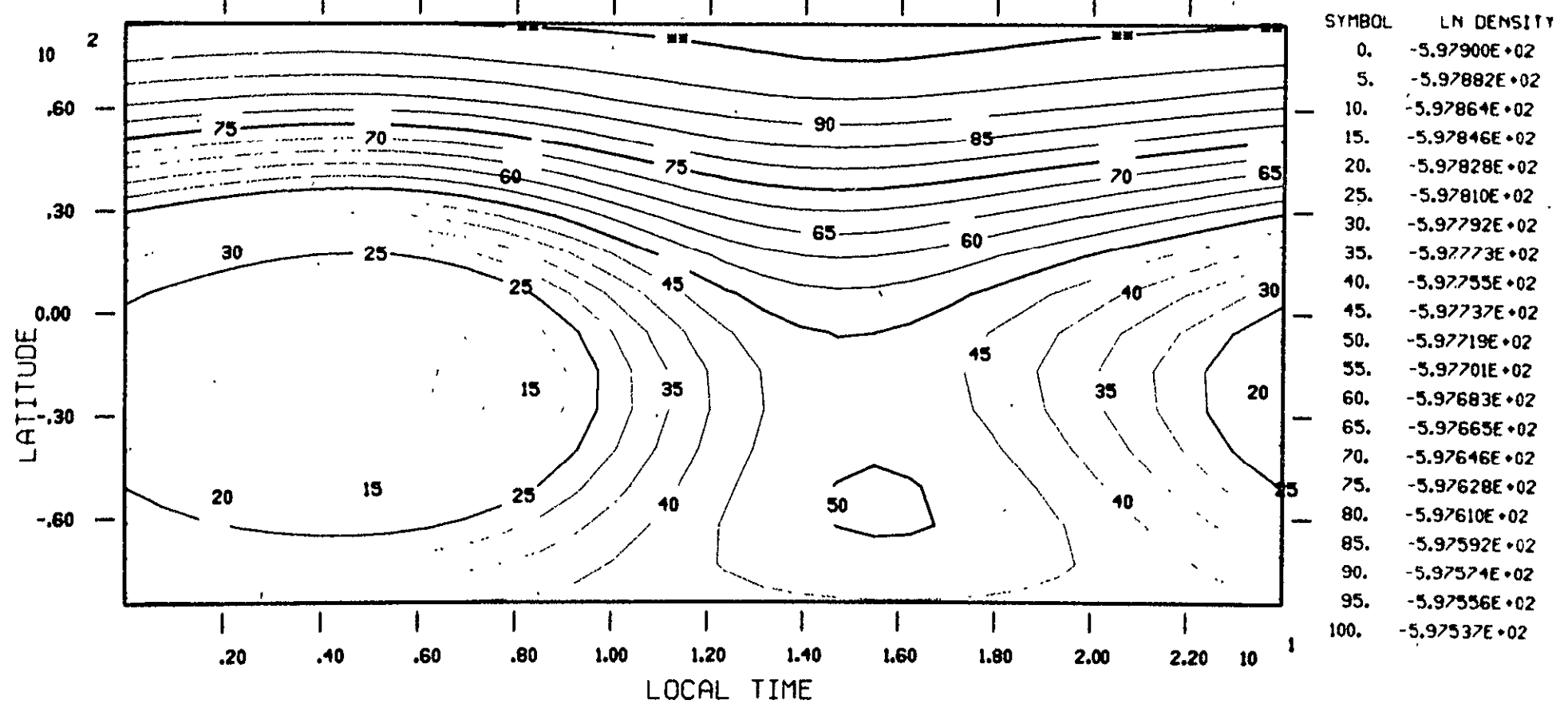
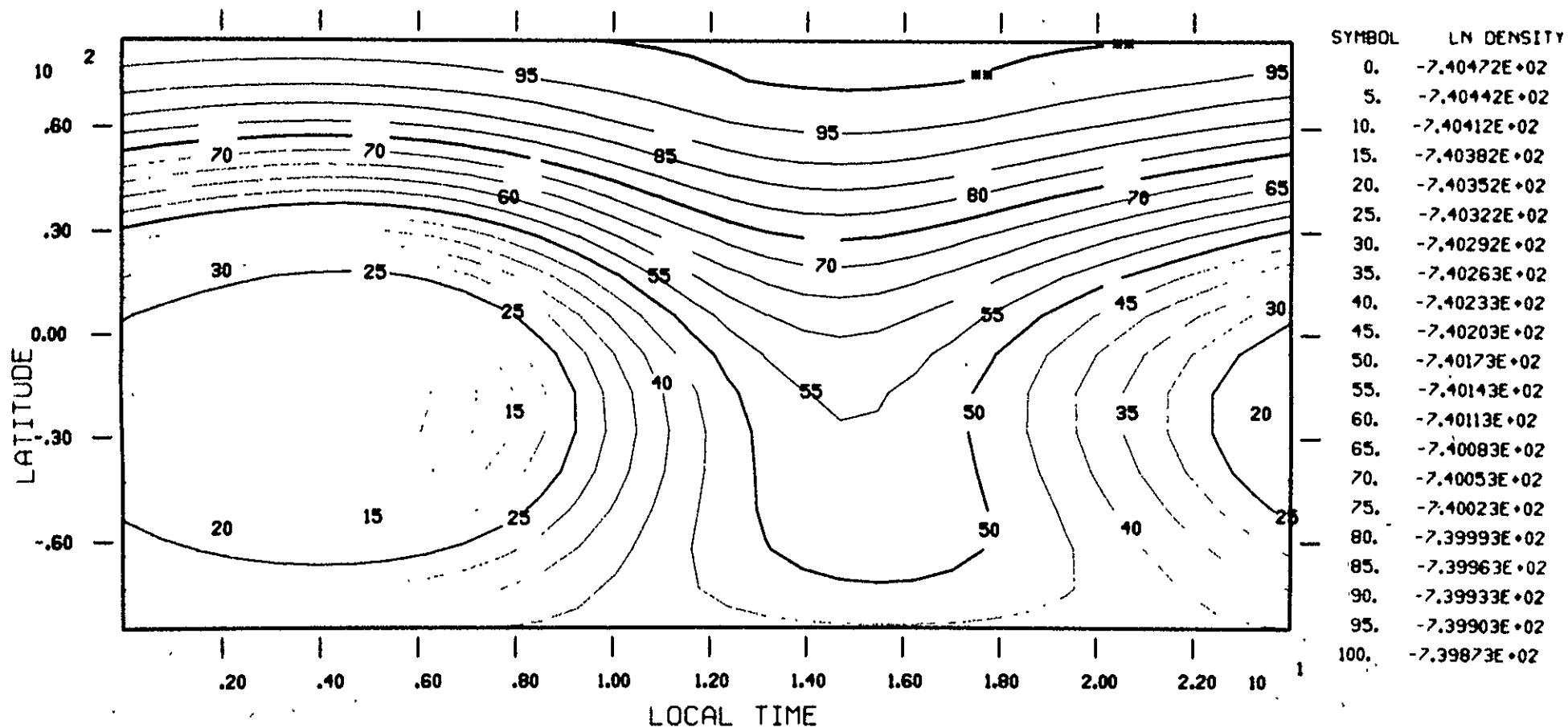


Fig
17a

ATMOSPHERIC DENSITY

MOLECULAR OXYGEN 143.0 KM 10.7 CM FLUX= 140.0 DAY 172.

CONTOUR LEVELS



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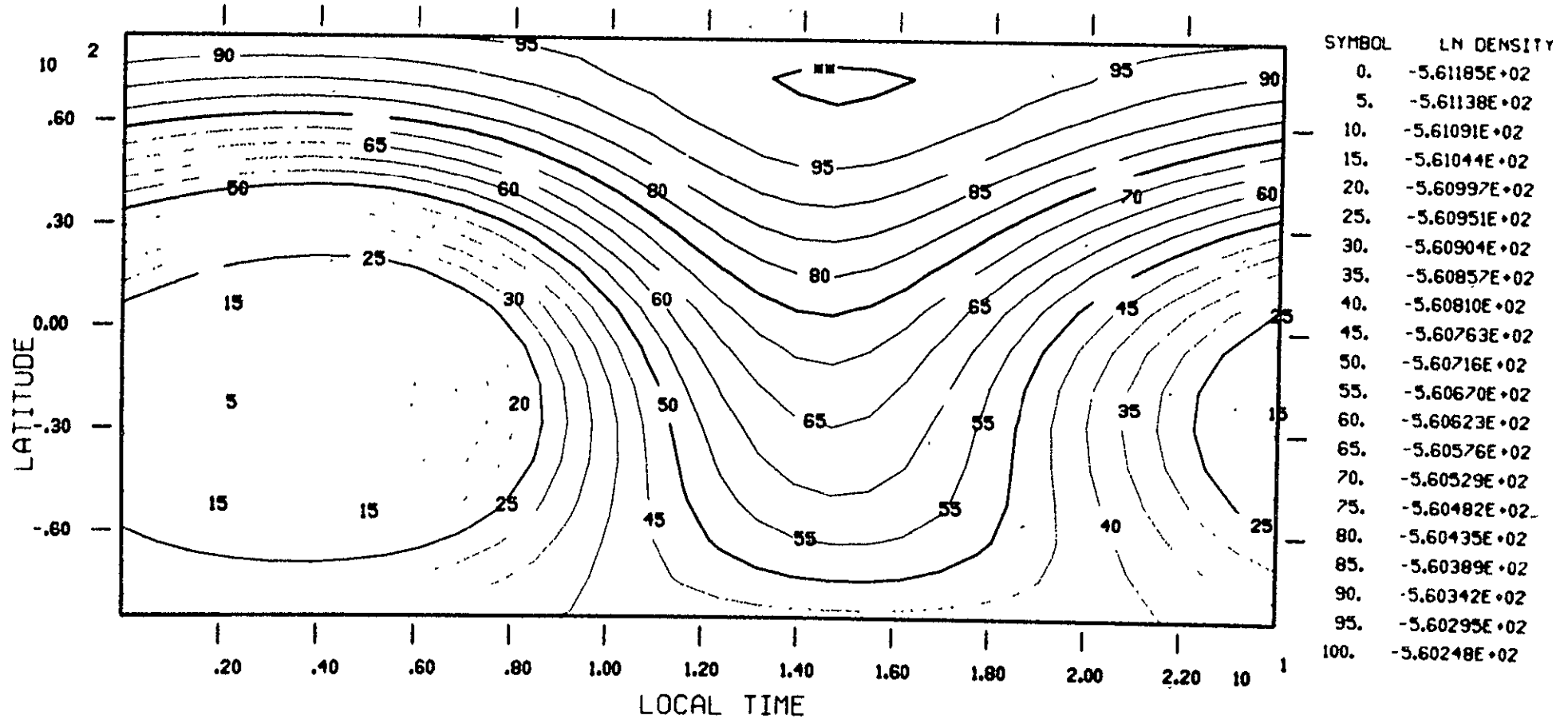
MOLECULAR OXYGEN

185.0 KM

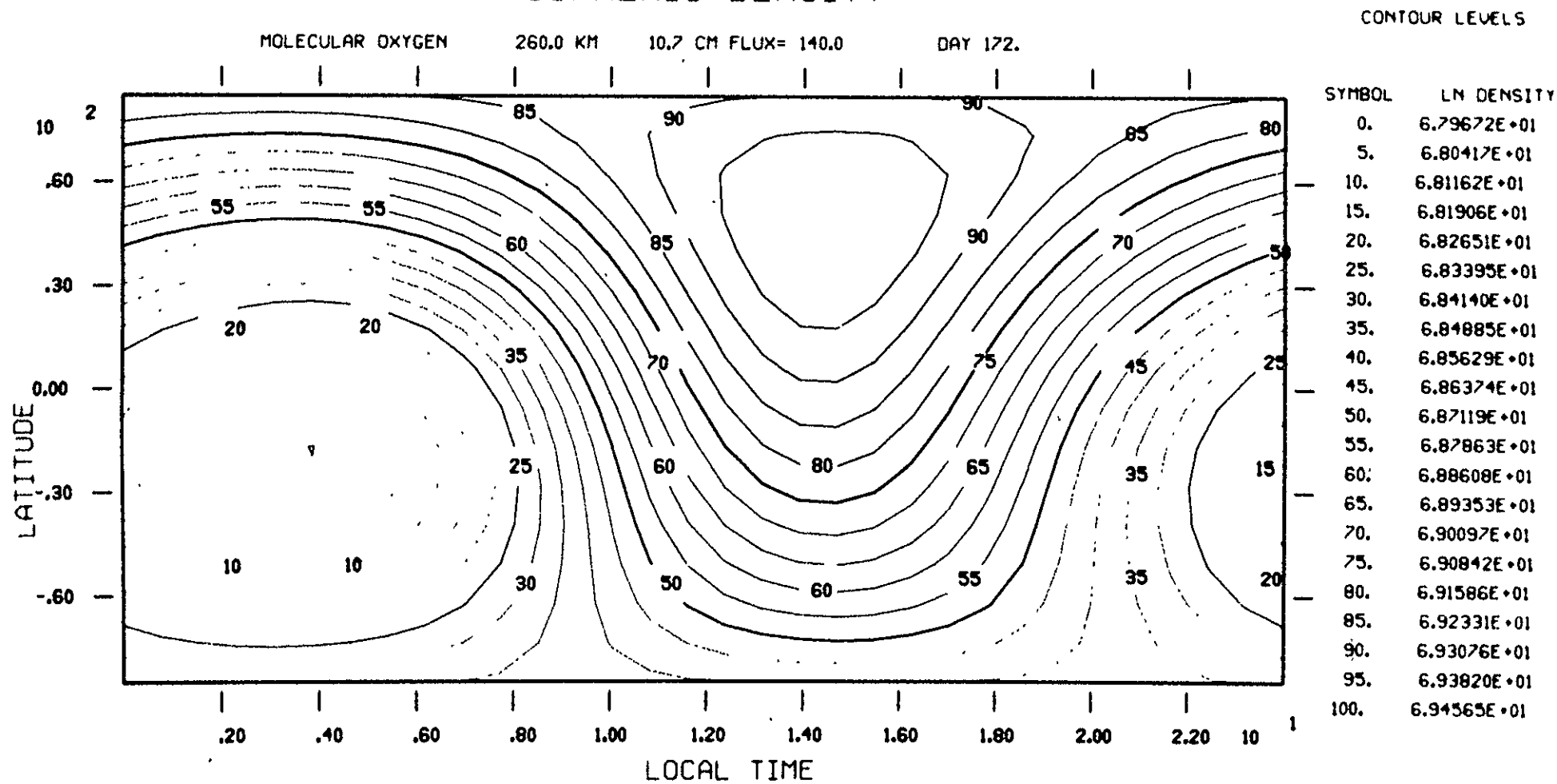
10.7 CM FLUX= 140.0

DAY 172.

CONTOUR LEVELS



ATMOSPHERIC DENSITY



ATMOSPHERIC DENSITY

MOLECULAR OXYGEN

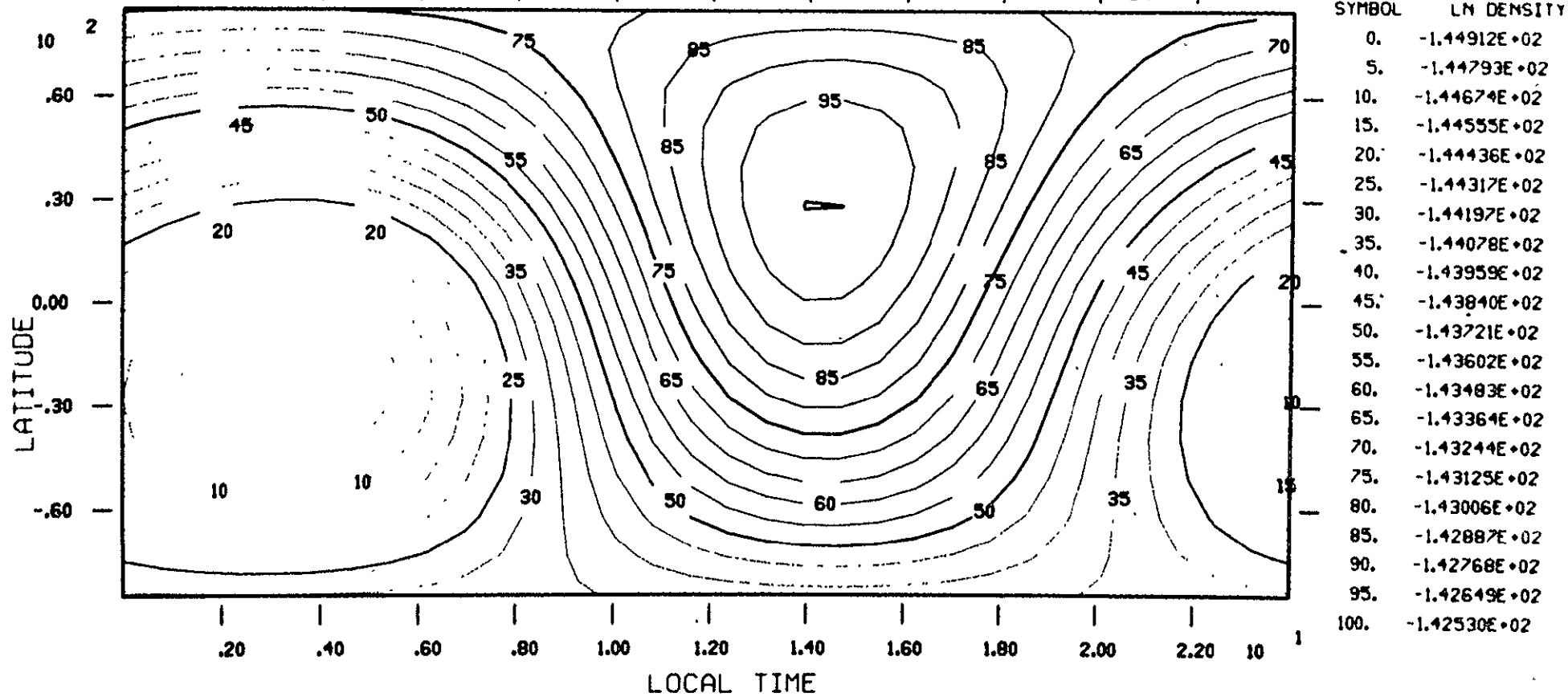
365.0 KM

10.7 CM FLUX= 140.0

DAY 172.

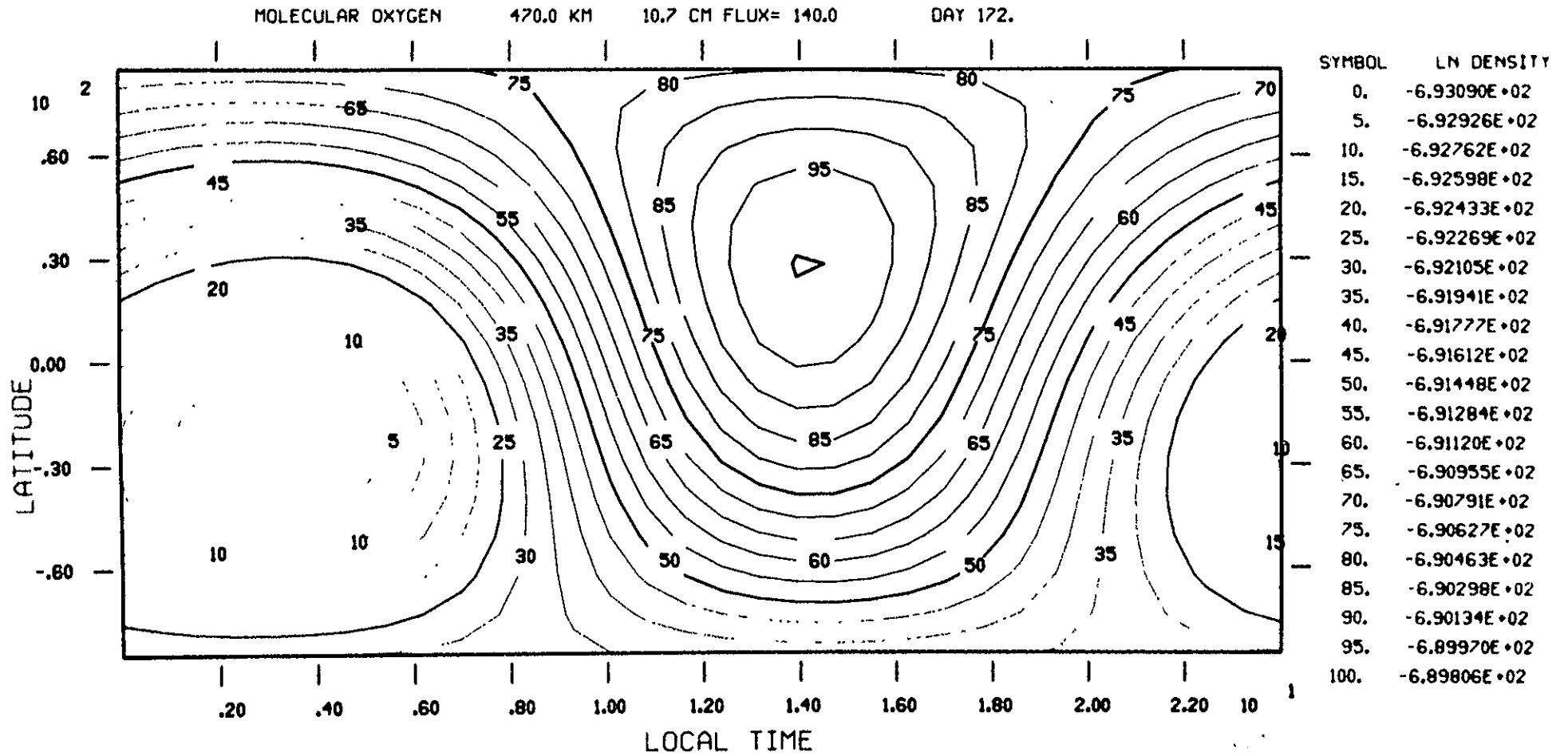
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ATMOSPHERIC DENSITY

CONTOUR LEVELS



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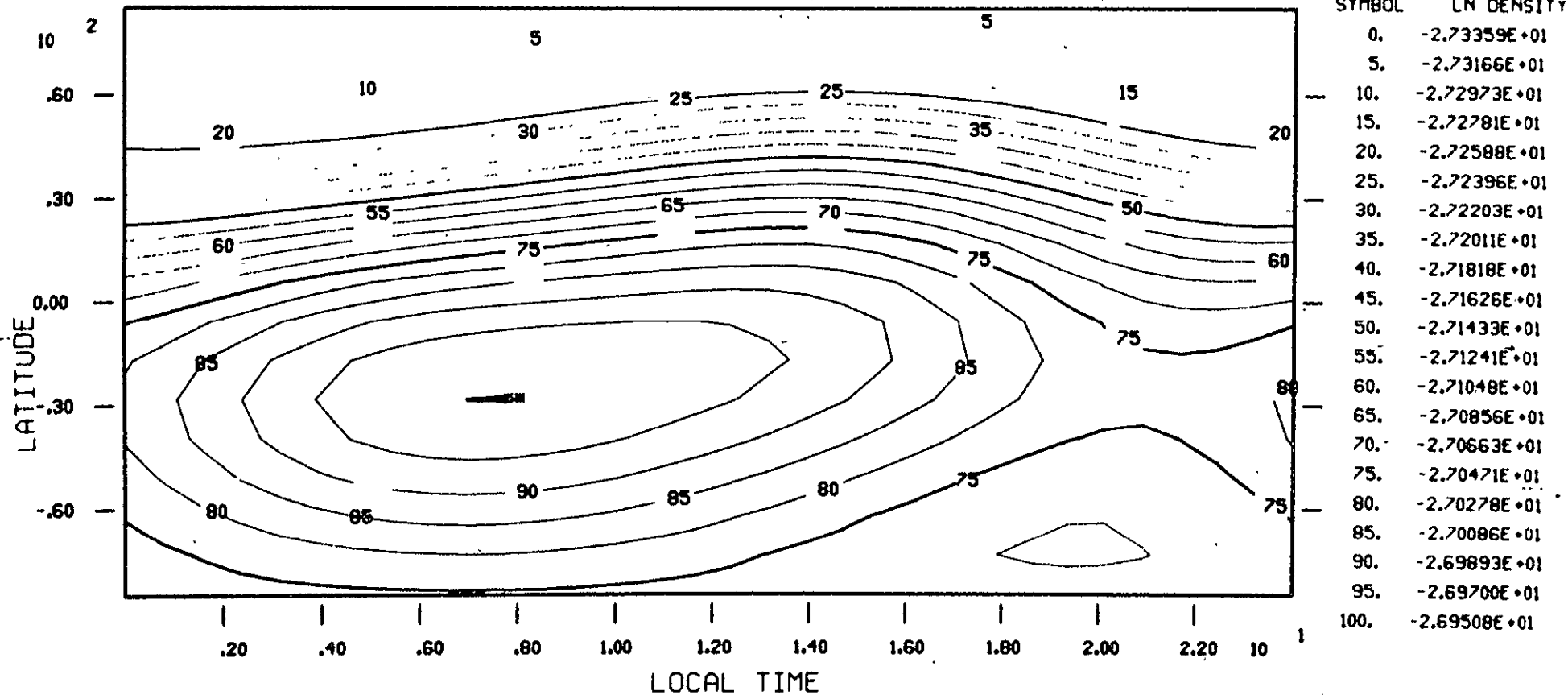
CONTOUR LEVELS

ATOMIC OXYGEN

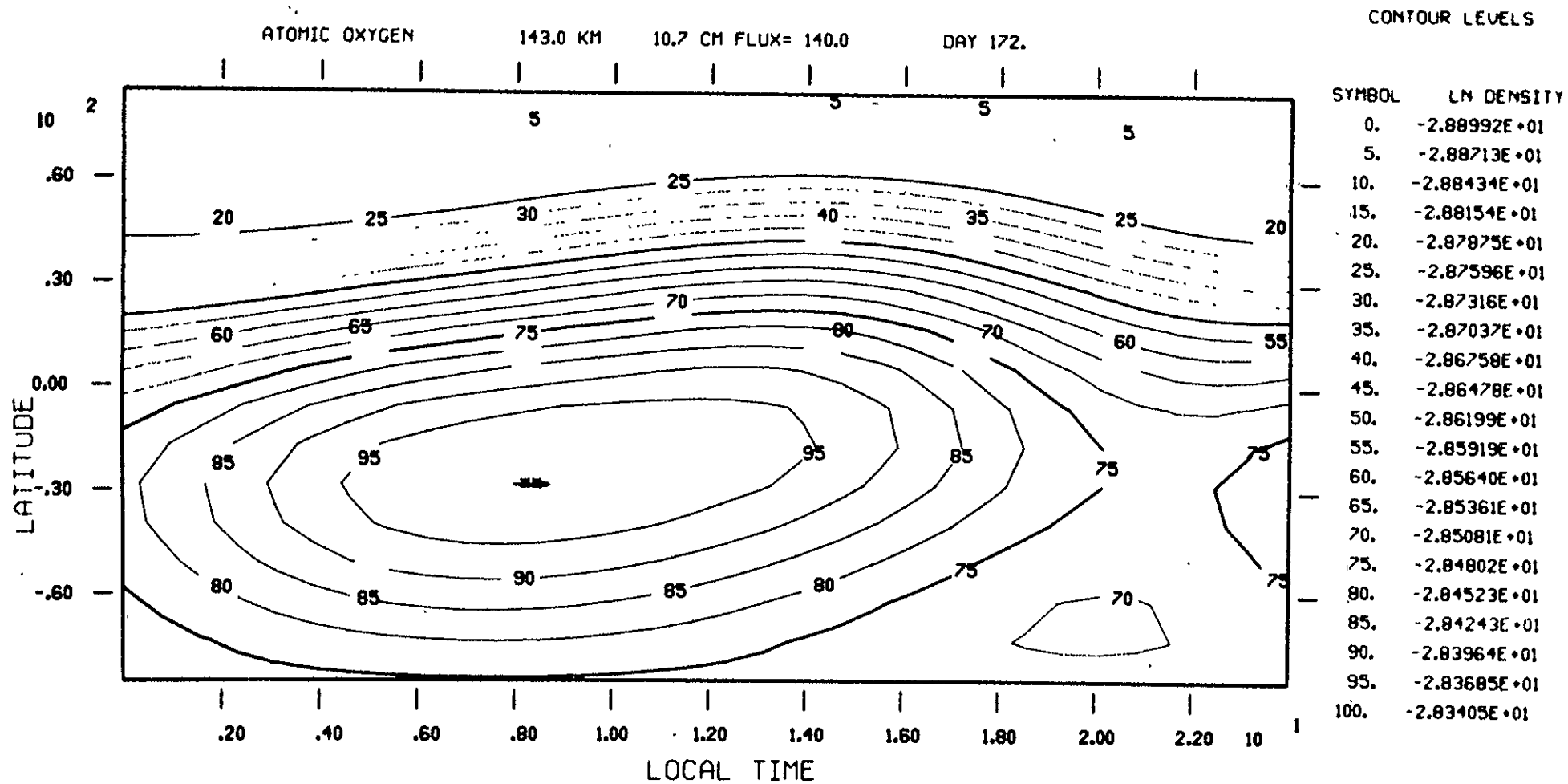
119.0 KM

10.7 CM FLUX= 140.0

DAY 172.



ATMOSPHERIC DENSITY



ATMOSPHERIC DENSITY

ATOMIC OXYGEN

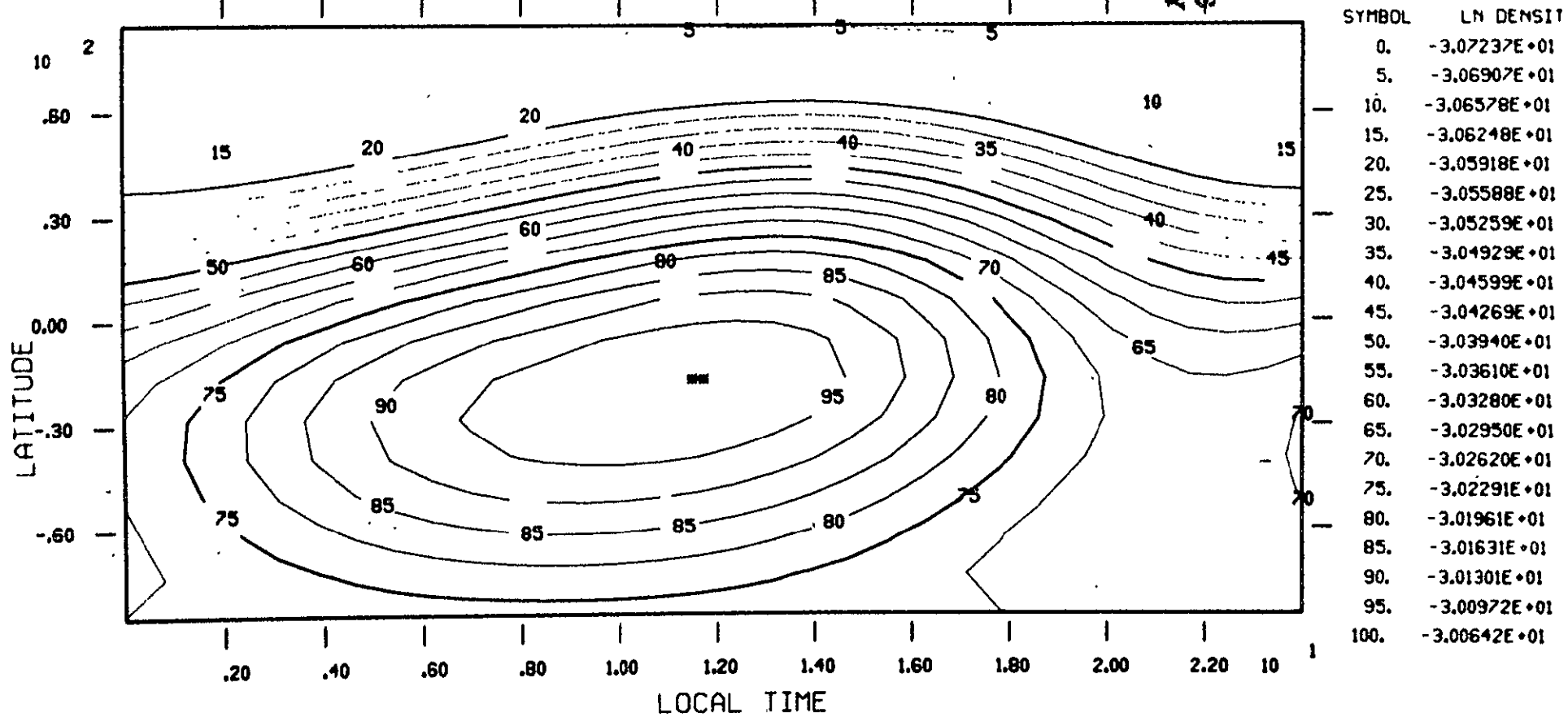
185.0 KM

10.7 CM FLUX= 140.0

DAY 172.

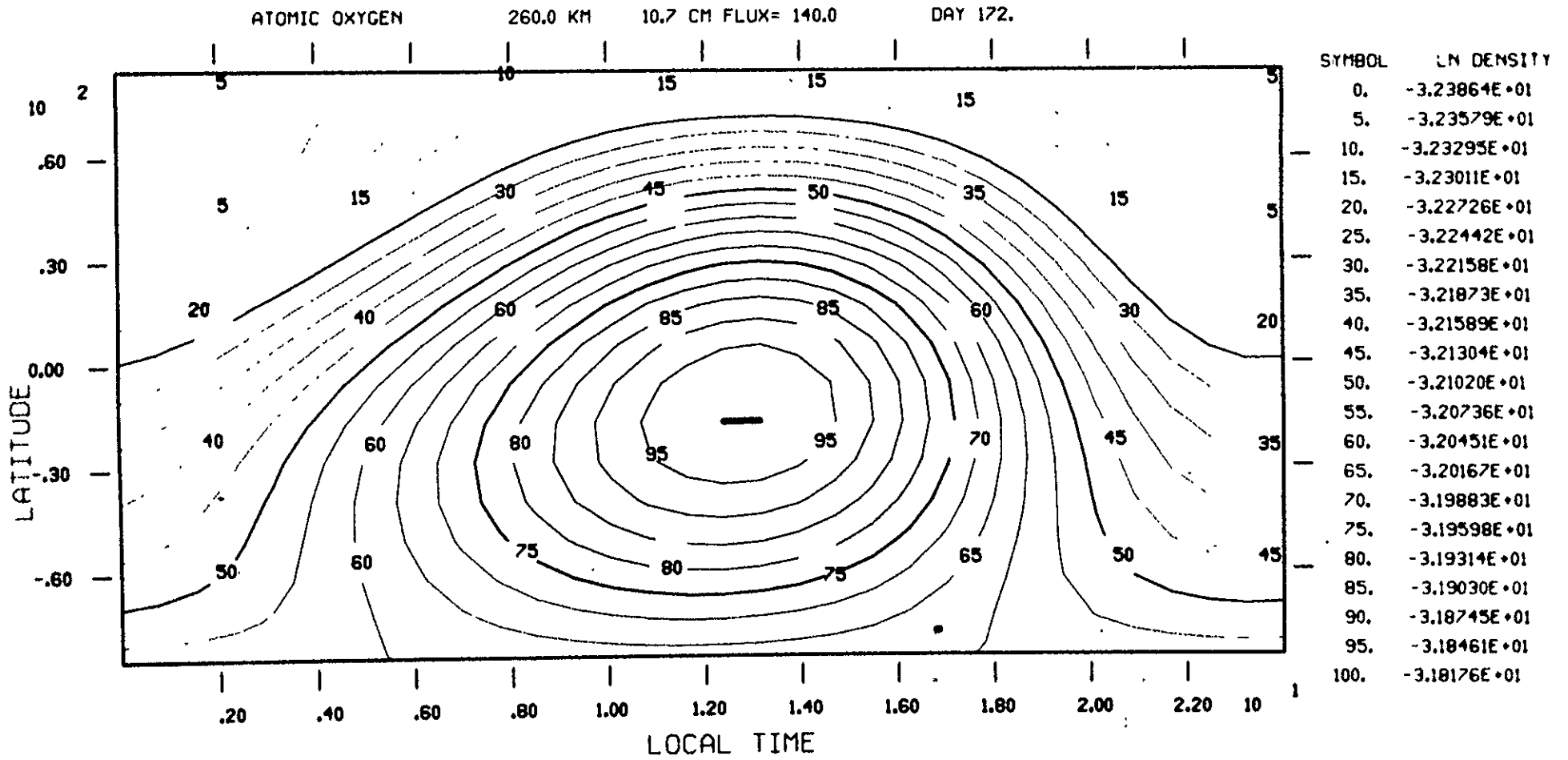
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CONTOUR LEVELS



ATMOSPHERIC DENSITY

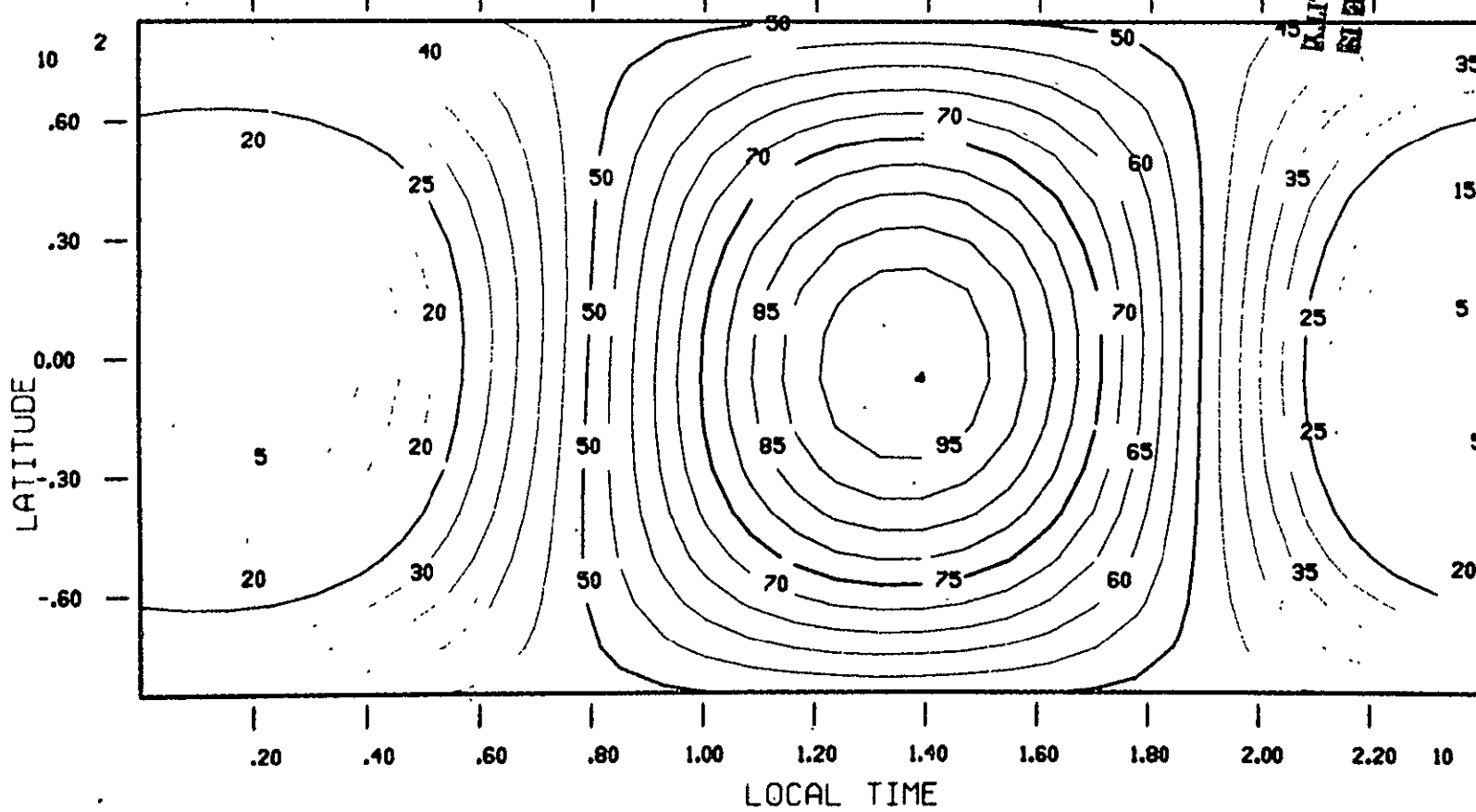
ATOMIC OXYGEN

365.0 KM

10.7 CM FLUX= 140.0

DAY 172.

CONTOUR LEVELS

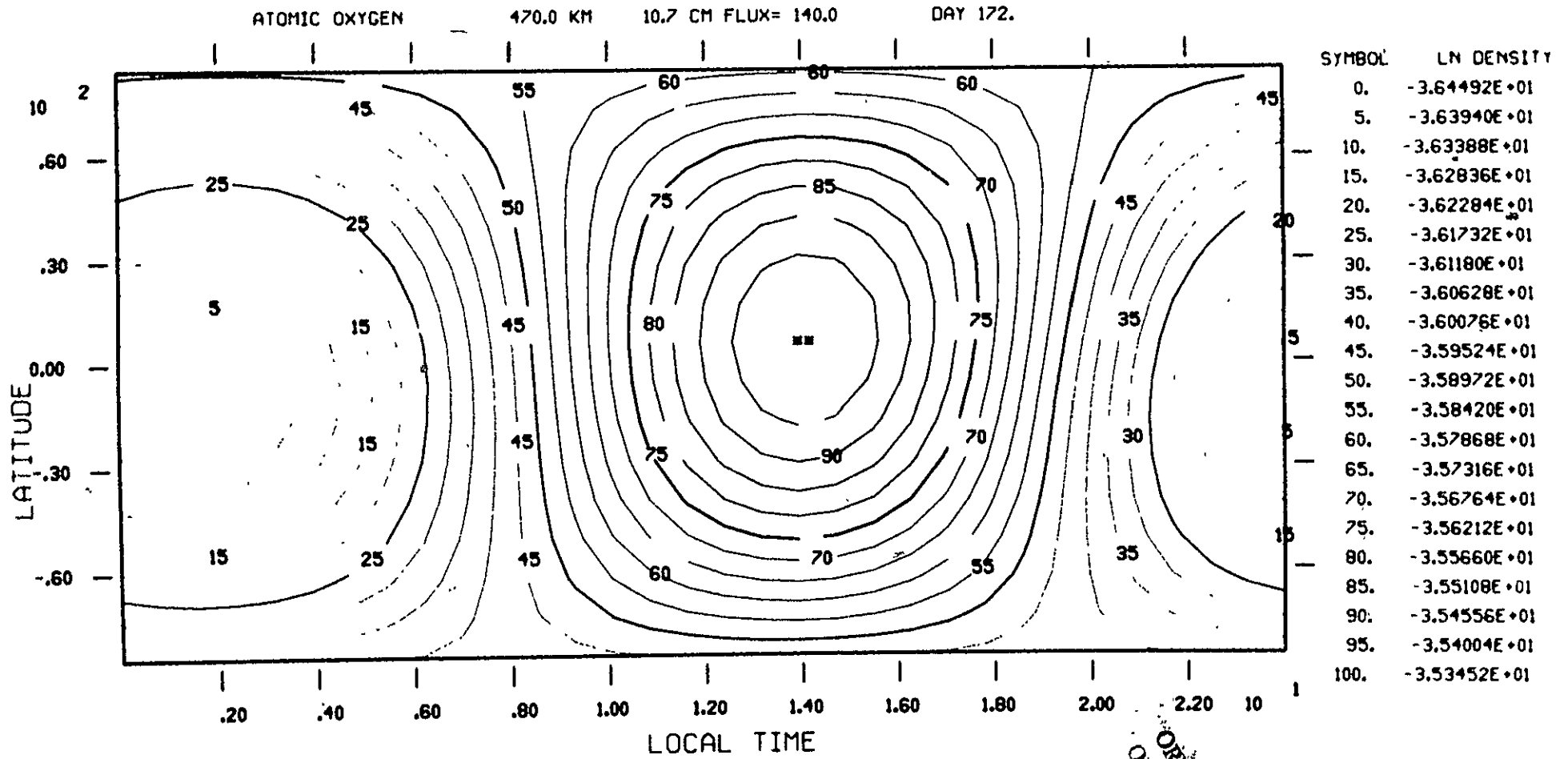


SYMBOL	LN DENSITY
0.	-3.42368E+01
5.	-3.42010E+01
10.	-3.41653E+01
15.	-3.41295E+01
20.	-3.40937E+01
25.	-3.40580E+01
30.	-3.40222E+01
35.	-3.39865E+01
40.	-3.39507E+01
45.	-3.39150E+01
50.	-3.38792E+01
55.	-3.38435E+01
60.	-3.38077E+01
65.	-3.37720E+01
70.	-3.37362E+01
75.	-3.37004E+01
80.	-3.36647E+01
85.	-3.36289E+01
90.	-3.35932E+01
95.	-3.35574E+01
100.	-3.35217E+01

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ATMOSPHERIC DENSITY

CONTOUR LEVELS



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